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Low Energy Low Background Photon Counter for WISP Search Experiments

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Physics beyond the Standard Model

The Standard Model is the theory which at present best summarizes the laws governing the behavior and the interactions of most known matter and radiation. It fails, however, to be a complete theory of fundamental interactions and elementary particles, since it does not include gravitation, dark matter and dark energy. For this reason, many see the need for a theory going beyond the Standard Model. This theory should unify weak, strong, electromagnetic and gravitational forces, and, in addition, solve the strong CP-Problem (*top-down motivation*). Conversely, recent astrophysical and cosmological observations regarding the evolution of the Universe, including also stellar evolution, can be explained with the introduction of new Weakly Interacting Sub-eV (light) Particles (WISPs), such as axions, Axion Like Particles (ALPs), MiniCharged Particles (MCP), chameleons and paraphotons, all of which are not included in the Standard Model (*bottom-up motivation*).

The best motivated theoretical extension of the Standard Model is string theory[1]. The main property of string theory (*top*) is that, to explain the observations (*down*), it needs at least one extra dimension which must be compactified with the other three space dimensions. This compactification gives rise to additional gauge sectors beyond the standard model. These sectors, called *hidden sectors*, give extra hidden $U(1)$ gauge bosons and hidden charged matter, such as paraphotons and minicharged particles[2]. Minicharged particles, for instance, have a charge smaller than one ($Q_f \ll 1$, in units of the electron charge), which is not necessarily an integer and it does not even to be a rational number. The mixing of these particles with electromagnetic photons is expressed by adding a kinetic-mixing term to the Standard Model Lagrangian:

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu} \quad (1)$$

where the first term is the $U(1)_{em}$ interaction, the second one is the $U(1)_{hidden}$ kinetic term, and the last term is the electromagnetic-hidden sector mixing term. χ is a dimensionless parameter in the range $10^{-16} \div 10^{-2}$.

The corresponding Lagrangian for paraphotons is[3]

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} - \frac{1}{2}\chi F^{\mu\nu}B_{\mu\nu} + \frac{1}{2}m_{\gamma'}B_{\mu}B^{\mu} + j_{\mu}A^{\mu} \quad (2)$$

where $m_{\gamma'}$ is the mass of the paraphoton. The most prominent implication of the kinetic-mixing term is that photons are no longer in a massless propagation mode.

The mixing term generates vacuum oscillations with a probability[4]:

$$P_{A-HS} = \sin^2(2\chi) \sin^2\left(\frac{m_{\gamma'}2L}{4\omega}\right) \quad (3)$$

where ω is the photon energy and L the oscillation length. This mixing term modifies the Coulomb potential of charge interactions. The expected mass of the paraphotons is in the μeV range. For lower masses, the contribution of the paraphotons is indistinguishable from that of the massless photons and for higher masses the contribution of paraphotons is exponentially suppressed.

Other particles outside the Standard Model are axions and, more generally, Axion Like Particles (ALPs). The axion, however, has also an independent origin in Quantum Chromodynamics (QCD). It was, in fact, first introduced to solve the strong CP problem and only later on its implications as a dark matter candidate were discovered. For this reason, among all the WISPs, it is the one which has the strongest theoretical motivation.

The energy scale f_a involved in WISPs physics is around 10^6 TeV, and, in addition, these particles interact very weakly with ordinary matter and radiation, it is thus very improbable that WISPs can be searched in the accelerator experiments, where the energies involved are of the order of a few TeV. On the other hand, *precision* experiments, in which very small effects, such as those due to the quantum vacuum properties, are studied, could shed light on these weakly interacting particles, thus becoming complementary to accelerator experiments.

Another way to motivate the need for new physics (*up*) is to start from astrophysical observations (*bottom*).

The oldest picture of the Universe is a dense hot plasma of elementary particles that expands against gravity. While the plasma was cooling, three long range interactions bound the particles in their present form. The color interaction confined quarks into hadrons, which then formed nuclei (Big Bang Nucleosynthesis), the Coulomb force combined nuclei and electrons into atoms and finally gravity formed galaxies, clusters and so on. These steps can be used to constrain the role of WISPs, although all the bounds obtained from astrophysical observations suffer from the fact that they are based on a production of WISPs in astrophysical objects which is not well known.

Big Bang Nucleosynthesis (BBN): the main element that can be used to constrain the new physics parameters is the observation of the present light nuclei abundance. After freezing, the reaction:

$$p + e^- \leftrightarrow n + \nu_e \quad (4)$$

became ineffective and the ratio $p/n=1/7$ was fixed. Then neutrons were bound into ${}^4\text{He}$ nuclei. The primordial abundance of helium-4 is used to constrain the non-standard energy density, ρ_x , expressed as a function of the effective number of thermal neutrino species. Only spin-zero particles are allowed to thermalize during BBN, while minicharged particles and massive photons cannot. The production of hidden photons is then suppressed with respect to other WISPs.

Cosmic Microwave Background (CMB): the blackbody shape of the cosmic microwave background spectrum was reached when the temperature of the Universe was a few keV. If WISPs were produced at that time, then their interactions with photons would have modified the background spectrum in a frequency-dependent way. This is used to test the existence of minicharged particles and paraphotons, setting a limit on m'_γ lower than 0.2 meV[5]. Moreover, thermal WISPs could contribute to the radiation energy density, delaying the matter-radiation equality and reducing their constant growth before decoupling. They act as standard neutrinos, thus more information about WISPs can be obtained from the neutrino spectrum.

Stellar evolution: the production of weakly interacting light particles inside the stellar core could affect the evolution of the star itself, contributing to the stellar energy loss by a factor

$$\left(\frac{d_{int}}{d_{surf}} \right)^n \left(\frac{T_{int}}{T_{surf}} \right)^m \quad (5)$$

with respect to the standard luminosity, where d_{int} and T_{int} are the stellar core density and temperature, while d_{surf} and T_{surf} are the stellar surface density and temperature. Stringent bounds are obtained in this way on ALPs, for instance, from the measurement of the amount of energy released during the cooling of a white dwarf. The transparency of the Universe to TeV photons from active galactic nuclei at cosmological distances may also be explained by back and forth oscillations of photons into Axion Like Particles.

Considering the renewed interest in this field of physics, the study and development of a low-energy system to search for weakly interacting light particles are discussed in this thesis. In particular, this work focuses on the search for Axion Like Particles. Among the different interactions of ALPs, the most promising for their detection, from an experimental point of view, is the coupling to two photons (Primakoff effect). Using this coupling, several bounds on ALP mass and energy scale have been set, and the current

best limits on the coupling, over a wide range of ALP masses, come from the the CAST (Cern Axion Solar Telescope) experiment at Cern, which looks for ALPs produced in the solar core. The experiment is based on the inverse of the Primakoff effect in a high magnetic field, where solar ALPs can be reconverted in photons. The regenerated photon flux is expected to be peaked at a few keV. On the other hand, there are suggestions that the problem of the anomalous temperature profile of the solar corona could be solved by a mechanism which could enhance the low-energy tail of the regenerated photon spectrum. A low energy photon counter has, for this reason, been designed and built to cover one of the CAST ports, at least temporarily. This system can also be applied, with proper upgrades, to other experiments searching for WISPs, such as the laboratory based experiments.

The detection system presented here consists of a Galilean telescope to match the CAST magnet bore cross section to an optical fiber leading photons to the sensors, passing first through an optical switch. This last device allows one to share input photons between two different detectors, and to acquire light and background data simultaneously. The sensors at the end of this chain are a photomultiplier tube and an avalanche photodiode operated in Geiger mode.

A set of measurements was carried out at Cern during 2007-2008. The background obtained was around 0.4 Hz (the same as that measured during the laboratory tests in Trieste), but it is clear that to progress from these preliminary measurements a lower background sensor is needed: for instance a Geiger mode avalanche photodiode (G-APD) cooled at liquid nitrogen temperature. The aim is to drastically reduce the dark count rate without losing in quantum efficiency. First results show that a reduction in background of a factor better than 10^4 is obtained, with no loss in quantum efficiency.

In the first chapter of this thesis a brief introduction to the theoretical motivations for WISP searches and in particular for axion searches are given. Furthermore, possible types of experiments to search for these particles are discussed.

The second chapter presents a detailed description of the CAST experimental apparatus and of the procedures applied during measurements runs.

The experimental apparatus developed for the detection of low-energy photons is reported in the third chapter. Two kinds of sensors are presented with their characteristics: a photomultiplier tube and an avalanche photodiode operated in Geiger mode.

The fourth chapter contains the results obtained in the measurements campaigns performed during 2007 and 2008 at CAST, along with the necessary apparatus developments.

The fifth chapter presents the evolution of the low-energy system with the introduction of a liquid nitrogen cooled Geiger mode avalanche photodiode. The goal of this

development is to reduce the dark count rate of the sensor without losing in quantum efficiency.

The conclusions and future developments of the system follow at the end.

Chapter 1

Axion theory and motivation

1.1 Axion origins

The axion is the oldest of the weakly interacting light particles introduced. Its origin, in fact, dates back to 1977, when Peccei and Quinn proposed the axion field as a solution for the strong CP problem related to the theory of Quantum ChromoDynamics (QCD)[6].

Quantum ChromoDynamics is the part of the Standard Model which studies the fundamental interaction (color interaction) among quarks and gluons. It is a non-Abelian gauge field theory^(a) of the SU(3) group^(b). Its quantum numbers are called flavor and color: the color number is used to build a local symmetry - a symmetry which acts independently in each space and time point - for the QCD theory.

The main dynamic equations of the theory are described by the QCD Lagrangian $\mathcal{L}_{QCD}$:

$$\mathcal{L}_{QCD} = \bar{\psi}(i\gamma^\mu \delta_\mu - m)\psi - g(\bar{\psi}\gamma^\mu \lambda_a \psi)G_\mu^a - \frac{1}{4}G_{\mu\nu}^a G_{\mu\nu}^a \quad (1.1)$$

where:

ψ is the quark field in the fundamental representation of the SU(3) group,

G_μ^a is the 8-gluon field,

γ^μ are the Dirac matrices,

λ_a are the generators of the SU(3) gauge group (Gell-Mann matrices),

$G_{\mu\nu}^a$ is the strong tensor equivalent of the $F_{\mu\nu}^a$ electroweak one:

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - gf^{abc}G_\mu^b G_\nu^c, \quad (1.2)$$

(f^{abc} are the structure constants of the SU(3) group).

In the limit of vanishing quark masses ($m_u, m_d \ll \Lambda_{QCD}$), $\mathcal{L}_{QCD}$ has a global symmetry

^(a)A field theory is a theory in which the Lagrangian is invariant under a group of local transformations.

^(b)The SU(3) group is the group of the 3x3 matrices with determinant 1 and dimension 8. The generators of the group are the Gell-Mann matrices which define the 8-gluons field.

for N quark flavors

$$SU(2)_L \times SU(2)_R \times U(1)_V \times U(1)_A \quad (1.3)$$

where, while the vector symmetry $U(1)_V$ is a good approximate symmetry of nature, the axial symmetry $U(1)_A$ is not. This is called the $U(1)_A$ problem: non conservation of this symmetry in strong interactions unless in the limit of vanishing quark masses. The solution was given by 't Hooft[7], who realized that the QCD vacuum has a more complicated structure, with a degenerate solution for the vacuum value. Associated to this structure of the QCD vacuum there is the phase parameter θ [8, 9]:

$$|\theta\rangle = \sum_n e^{-in\theta} |n\rangle, \quad (1.4)$$

where $|n\rangle$ is the number classifying the various vacua. However, if this term solves the $U(1)_A$ problem, restoring the symmetry, it creates a new one since it adds a new term in the QCD Lagrangian:

$$L_\theta = \theta \frac{g_s^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}. \quad (1.5)$$

This term violates both the parity symmetry^(c) and the time reversal invariance, but does not violate C symmetry^(d), thus producing a CP-violation. The "strong CP problem" is then the non observation of CP symmetry breaking in QCD fields as expected.

The non-zero expectation value for the QCD vacuum induces, moreover, a neutron electric dipole moment, which, if $\theta \approx 1$, is larger than:

$$d_n \simeq \frac{e\theta m_q}{m_N^2} \simeq 10^{-17} \text{ e} \cdot \text{cm}. \quad (1.6)$$

Experimental results obtained in 1951 by Purcell and Ramsey showed that $d_n < 3 \cdot 10^{-20} \text{ e} \cdot \text{cm}$ [10], so if θ exists it must be smaller than 1. The present bound on the electric dipole moment of neutron is $d_n < 3 \cdot 10^{-26} \text{ e} \cdot \text{cm}$ [11], which implies $\theta \lesssim 10^{-9}$. The question is then *why is this $\bar{\theta}$ angle^(e), coming from the strong and weak interaction, so small?*[6].

To answer this question the Peccei-Quinn mechanism was introduced. In this mechanism θ is no longer a parameter of the standard model, but a dynamical CP-conserving field, and the $U(1)_{PQ}$ global chiral symmetry, spontaneously broken at a scale f_a , is introduced. This new chiral symmetry, $U(1)_{PQ}$, has the Lagrangian:

$$\mathcal{L}_{eff} = \mathcal{L}_{QCD} + i \cdot \mathcal{L}_a = \mathcal{L}_{QCD} + \frac{a}{f_a} \xi \frac{g^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\mu\nu}, \quad (1.7)$$

where ξ [12] is a model-dependent term given by $\xi = \frac{4}{3} \left(\frac{E}{N} - \frac{2}{3} \frac{4+z}{1+z} \right)$, where E/N represents the ratio between the electromagnetic and the color anomaly, and $z = m_u/m_d$ is

^(c)Spontaneous flip of the spatial coordinate.

^(d)Physical laws do not change under charge conjugation.

^(e) $\bar{\theta} = \theta + \text{Arg Det } M_q$, where M_q is the quark mass matrix.

the up/down quark mass ratio. This newly added term violates P and T symmetries, but conserves C-symmetry, thus violating CP.

The spontaneous symmetry breaking can also be interpreted as the birth of a new Nambu-Goldstone boson, which was called *AXION* by Wiczek[13] – “...I called this particle the *axion*, after the laundry detergent, because that was a nice cutely name that sounded like a particle and because this particle solved a problem involving axial currents...” –. The vacuum expectation value of the QCD Lagrangian is then related to the minimum of the *axion potential* which is invariant under the $a \rightarrow a + 2\pi f_a$ transformation. Solving for a minimum of the effective potential V_{eff} , obtained for $\langle a \rangle = -\frac{\bar{\theta} f_a}{\xi}$, an expectation value for the axion mass is found[6]:

$$m_a = \sqrt{\left\langle \frac{\partial^2 V_{eff}}{\partial a^2} \right\rangle} = \frac{z^{1/2}}{1+z} \frac{f_\pi m_\pi}{f_a} = 6.3 \text{eV} \frac{10^6 \text{GeV}}{f_a} \quad (1.8)$$

where m_π is the pion mass and f_π is the pion decay constant. From eq.1.8 it is clear that once f_a is fixed, the axion mass is no longer a free parameter and vice versa, and, moreover, that the axion mass depends on the Peccei-Quinn scale f_a as the pion mass depends on the pion decay scale for the nuclear interactions.

1.2 Axion properties

<i>Axion</i>	
Interaction:	Gravity, Electromagnetic
Status:	Hypothetical
Theorized:	1977, Peccei and Quinn
Mass:	10^{-6} to $1 \text{ eV}/c^2$
Electric charge:	0
Spin:	0

Figure 1.1: Page from the wikipedia free encyclopedia which summarizes the known properties of the axion.

Concerning axion dynamics, there is the distinction between two general categories[6, 14]: the visible axions and the invisible axions. The first model assumes that axions are massive Nambu-Goldstone bosons and that the value of f_a coincides with the electroweak scale $f_{EW} = (\sqrt{2}G_F)^{-1/2}$, where G_F is the Fermi constant and $f_{EW} = 250 \text{ GeV}$. In this massive axion scenario, two Higgs fields are introduced to make the $\mathcal{L}_{QCD}$ invariant under $U(1)_{PQ}$ symmetry. Each field has its own vacuum expectation value $\mathcal{V}_1$ and

$\mathcal{V}_2$:

$$\phi_1 = \frac{\mathcal{V}_1}{\sqrt{2}} e^{iax/\mathcal{V}_F} \begin{pmatrix} 1 \\ 0 \end{pmatrix} \quad \phi_2 = \frac{\mathcal{V}_2}{\sqrt{2}} e^{iax/\mathcal{V}_F} \begin{pmatrix} 0 \\ 1 \end{pmatrix} \quad (1.9)$$

where $x = \mathcal{V}_2/\mathcal{V}_1$ and $\mathcal{V}_F = \sqrt{\mathcal{V}_1^2 + \mathcal{V}_2^2}$, giving

$$m_a = 25N_g \left(x + \frac{1}{x} \right) \simeq 200 \text{keV} \quad (1.10)$$

with N_g the number of effective families for the interaction with 2 photons and 2 fermions. Axions of this kind are ruled out by experiments. For instance, if the axion has a mass of that order, the Branching Ratio $BR(K^+ \rightarrow \pi^+ + a)$ should be $3 \cdot 10^{-5}(x + \frac{1}{x})^2$, well above the measured limit of $3.8 \cdot 10^{-8}$ [6].

The scenario which still survives to this day, is the "invisible" axion model, in which axions are weakly interacting light particles. In this situation $f_a \gg f_{weak}$ and the vacuum expectation value could be larger. There are two main "invisible" axion models, depending on the axion interaction with the other particles:

1. KSVZ (Kim-Shifman-Vainshtein-Zakharov) in which axions do not interact with leptons but only with nucleons and photons,
2. DFSZ (Dine-Fischler-Srednicki-Zhitnitskii) in which all the interactions are considered.

1.2.1 KSZV model

In this model a heavy quark, with $M_Q \sim f_a$, and a scalar field ϕ , with $f_a = \langle \phi \rangle \gg \mathcal{V}_F$, are added to the Peccei-Quinn mechanism. The PQ-charge is not carried by quarks or leptons but by the introduced heavy quark. There is only strong interaction with nucleons, while the weak interaction with leptons is not allowed. The resulting Lagrangian has an interaction, a kinetic and a potential term [15]:

$$\mathcal{L} = \left(\frac{i}{2} \bar{\Psi} \partial_\mu \gamma^\mu \Psi \right) + \partial_\mu \Phi^\dagger \partial^\mu \Phi - V(|\Psi|) - h(\bar{\Psi}_L \Psi_R \Phi) = \mathcal{L} + \mathcal{L}_{axion}^{KSVZ}, \quad (1.11)$$

where

$$\mathcal{L}_{axion}^{KSVZ} = \frac{a}{f_a} \left(\frac{g_s^2}{32\pi^2} G_b^{\mu\nu} \tilde{G}_{b\mu\nu} + 3e_Q^2 \frac{\alpha}{4\pi} F^{\mu\nu} \tilde{F}_{\mu\nu} \right) \quad (1.12)$$

where e_Q is the electromagnetic charge of the heavy quark. The couplings to nucleons and photons of axions, belonging to this model, are expressed in the following form [14]:

$$\begin{aligned}
 g_{ap} &= \frac{C_p m_p}{f_a} = -6.01 \cdot 10^{-8} \text{meV}, \\
 g_{an} &= \frac{C_n m_n}{f_a} = -0.69 \cdot 10^{-8} \text{meV}, \\
 g_{a\gamma\gamma} &= -\frac{a}{2\pi f_a} \left(\frac{E}{N} - \frac{2(4 + m_u/m_d + m_u/m_s)}{3(1 + m_u/m_d + m_u/m_s)} \right), \\
 &= -\frac{a}{2\pi f_a} \left(\frac{2(4 + m_u/m_d + m_u/m_s)}{3(1 + m_u/m_d + m_u/m_s)} \right).
 \end{aligned} \tag{1.13}$$

where the indexes p, n, u, d and s refers to protons, neutrons, up quarks, down quarks and strange quarks respectively.

1.2.2 DFSZ model

In this model axion can interact both with quarks and leptons. The difference with respect to the previous model is that only the scalar field ϕ , with $f_a = \langle \phi \rangle \gg \mathcal{V}_F$, and two electroweak doublets ϕ_1 and ϕ_2 are introduced in the PQ mechanism[8]. Since each field has its own expectation value, it is allowed to introduce a mixing angle β among them. The coupling coefficients follow the same equations as in the KSVZ model but with the introduction of the mixing angle:

$$\begin{aligned}
 g_{ap} &= \frac{C_p m_p}{f_a} = [-0.10 - 0.45 \cos^2 \beta] \times \frac{m_p}{f_a}, \\
 g_{an} &= \frac{C_n m_n}{f_a} = [-0.18 + 0.39 \cos^2 \beta] \times \frac{m_n}{f_a}, \\
 g_{a\gamma\gamma} &\simeq -0.75 \frac{\alpha}{2\pi f_a}, \\
 g_{aee} &= 0.85 \cdot 10^{-10} \text{meV} \frac{\cos^2 \beta}{N_f}.
 \end{aligned} \tag{1.14}$$

1.3 Coupling constants of axions

Axion coupling to matter and radiation depends on the model chosen to describe axion properties, even if the dependence is very weak (see section 1.2). The properties of axion couplings are derived in analogy to the corresponding pion properties as field boson for the nuclear interactions. There are interactions with gluons, with photons, with fermions and, in some model, with electrons.

Coupling to gluons This is the mechanism by which the axion acquires mass. The way in which axions couple to gluons (fig.1.2) is different with respect to all other pseu-

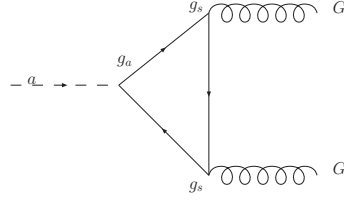


Figure 1.2: Feynman diagram of the axion-gluon coupling. Figure taken from [15]. (See text)

doscalar particles and is not model dependent:

$$\mathcal{L}_{aG} = \alpha_s \frac{1}{8\pi f_a} a G_a^{\mu\nu} \tilde{G}_{a\mu\nu} = \frac{g_s^2}{4\pi} \frac{g_a}{8\pi m_f} a G_a^{\mu\nu} \tilde{G}_{a\mu\nu} \quad (1.15)$$

where g_s is the strong interaction coupling constant, g_a the corresponding axion-fermion one and m_f the mass of the fermion involved in the interaction. Axion particles mix with the Yukawa boson for the strong interaction, the pion, and pick up a small mass following the relation:

$$f_a m_a \sim f_\pi m_\pi \quad (1.16)$$

The axion mass is thus defined as:

$$m_a = 6.0 \text{eV} \frac{10^6 \text{GeV}}{f_a}. \quad (1.17)$$

Coupling to photons The interaction of the axion field with two photons (see fig.1.3) is possibly the most important from an experimental point of view. The effective Lagrangian for the axion field a is written as[16]:

$$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} a = -g_{a\gamma\gamma} \vec{E} \cdot \vec{B} a \quad (1.18)$$

where F is the electromagnetic tensor and $\vec{E}$ and $\vec{B}$ the electric and magnetic field respectively. The coupling constant is defined as follows:

$$g_{a\gamma\gamma} = \frac{\alpha}{2\pi f_a} C_\gamma = \frac{\alpha}{2\pi} \left[\frac{E}{N} - \frac{2(4+z)}{3(1+z)} \right] \frac{1+z}{z^{1/2}} \frac{m_a}{m_\pi f_\pi}, \quad (1.19)$$

where the ratio E/N depends on the model, if it is KSVZ then $E/N \sim 0$, if it is DFSZ then $E/N \sim 8/3$. The branching ratio of the decay of a into two photons is:

$$\Gamma_{a\gamma\gamma} = \left[\frac{\alpha}{16\pi^{3/2}} \left[\frac{E}{N} - \frac{2(4+z)}{3(1+z)} \right] \right]^2 \left(\frac{1+z}{z^{1/2}} \right)^2 \frac{m_a^5}{m_\pi^2 f_\pi^2} \quad (1.20)$$

which means that the axion time decay constant will be comparable to the age of the Universe only if $m_a \gtrsim 20 \text{ eV}$.



Figure 1.3: Feynman diagrams for the axion-photon coupling. *Left:* the most general axion-photon loop diagram (at left figure taken from [14]). *Right:* the coupling of axion to photons is via a triangle loop in which fermions carry both the PQ-charge and the electromagnetic charge (at right figure taken from [15]).

Coupling to fermions The interaction with fermions f is invariant under $a \rightarrow a + a_0$:

$$\mathcal{L}_{af} = \frac{C_f}{2f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu a \quad (1.21)$$

where $g_{af} = \frac{C_f m_f}{f_a}$ is the coupling constant to fermions. It is different depending whether the PQ-charge is carried by electrons or nucleons.

- The electron can carry the PQ-charge only in the DFSZ model since in the KSVZ model the axion-electron interactions are not allowed, then the only relevant term in the Lagrangian of equation 1.21 is a tree-level coupling. The one-loop level coupling also exists but it is negligible with respect to the tree level one. g_{aee} is given by eq.1.14.
- The axion-nucleon coupling is model independent. A general expression for the axion-nucleon coupling coefficient is:

$$\begin{aligned} C_p &= (C_u - \eta) \Delta u + (C_d - \eta z) \Delta d + (C_s - \eta m_u/m_s) \Delta s \\ C_n &= (C_u - \eta) \Delta d + (C_d - \eta z) \Delta u + (C_s - \eta m_u/m_s) \Delta s \end{aligned} \quad (1.22)$$

where $\eta = (1 + z + m_u/m_s)^{-1}$ and Δ_{quark} is the helicity contribution of nucleons carried by quarks[16].

1.4 Cosmological and astrophysical bounds on axion mass and coupling

Astrophysics and cosmology play an increasing role in the study of particle physics, since they offer a window on a natural laboratory where particle processes of all kinds are occurring, or have occurred in the past. For instance, since axions interact with matter

like other Nambu-Goldstone bosons, it can be safely assumed that the evolution of the Universe, including stellar evolution, were and are influenced by the presence or the absence of these weakly interacting particles. The production of axions could for example accelerate the consumption of stellar fuel, since they represent a form of energy loss. Astrophysical and cosmological observations can then be used to set bounds on the mass and the couplings of the axion[17].

1.4.1 Cosmological bounds

The evolution of the Universe related to the presence of axions is strictly connected to the primordial soup environment. There are two different scenarios[18]:

1. thermal axion production (Hot Dark Matter - HDM),
2. cold axion production (Cold Dark Matter - CDM).

Thermal axions

From cosmology it is known that a particle is in thermal equilibrium if its interaction rate with the other particles is larger than the cooling time of the Universe:

$$\Gamma_{axion} = \sum_i n_i \langle \sigma_i v \rangle \geq H \quad (1.23)$$

where n_i is the axion density, σ_i the interaction cross section, v the average velocity and H indicates the Hubble constant $\dot{a}(t)/a(t)$ with $a(t)$ the scale factor. If the axion scale f_a is sufficiently small ($f_a \lesssim 4 \cdot 10^7 \text{ GeV}$), so that the coupling constant is sufficiently large, there is the possibility of thermal axion production in the early Universe.

The main interaction of axions for the purpose of thermalization is:

$$N + N \leftrightarrow N + N + a. \quad (1.24)$$

In practice nucleons are so rare in the early Universe with respect to pions, that only the axion-pion interaction will be relevant for thermalization purposes:

$$\pi + a \leftrightarrow \pi + \pi. \quad (1.25)$$

When the condition of equation 1.23 is no longer satisfied then axion ceases interacting with matter and radiation and enters decoupling phase. The temperature at which this happens, is $T_D < T_{QCD} \simeq 200 \text{ MeV}^{(f)}$, at this temperature both photons and neutrinos

^(f)If it was considered f_a sufficiently small, and anyhow smaller than 10^{12} GeV .

are still in thermal equilibrium with matter and radiation. Since axions are decoupled after T_D , they do not feel the energy released from the electron-positron annihilation at $T_\gamma = 0.5$ MeV, and start to dilute. The present HDM expected density is:

$$n_a^{th} = \frac{\zeta(3)}{\pi^2} T_D^3 \left(\frac{R_D}{R_0} \right)^3, \quad (1.26)$$

where R_D/R_0 is the ratio of the scale factors at T_D and now, and

$$n_a = \frac{g_*(T_0)}{g_*(T_D)} \frac{n_\gamma}{2} \quad (1.27)$$

where g_* is the number of relativistic degrees of freedom. The contribution of axions to non-barionic dark matter is defined as:

$$\Omega_a h^2 = \frac{m_a}{131 \text{eV}} \frac{10}{g_s^*}, \quad (1.28)$$

where m_a is the axion mass, Ω_a is the density parameter, h is the parametric definition of the Hubble constant $h = H_0/(100 \text{ (km/s)/Mpc})$, and g_s^* is the effective number of degrees of freedom for relativistic particles. With the present information from WMAP and CMB it is possible to conclude that $m_a < 0.42$ eV, and $\Omega_a h^2 < 0.0014$, a small part of the total cold dark matter ($\lesssim 2.5\%$) (see fig.1.4)[19].

Cold axions

The main processes that are involved in the production of cold axions are string and vacuum misalignment. If the condition $f_a \leq 10^8$ GeV is not satisfied then $T_D > T_{QCD}$, axions thermalize before QCD freeze out, and the vacuum misalignment process must be taken into account. In this scenario axions are massless and the value of their potential is different in different points of the Universe. In the first phase, when the temperature fell below f_a , the axion potential turned on, with all values of $\bar{\Theta}$ (misalignment angle) equally probable. The second phase started when $T < T_{QCD}$ (see fig.1.5), the axion became massive and the axion field started to approach its minimum. However, the axion field did not reached the minimum, rather it oscillated around it until $H < m_a$. In this scenario[20]:

$$\Omega_{mis} h^2 = 0.105 \Theta_i^2 \left(\frac{10 \mu\text{eV}}{m_a} \right)^{1.184}, \quad (1.29)$$

where Ω_{mis} is the misalignment axion relative density and Θ_i is the initial angle.

It is worth noting that while in the thermal axion production the Ωh^2 term is proportional to m_a , in the cold axion case it is proportional to $\frac{1}{m_a}$ (see fig.1.6).

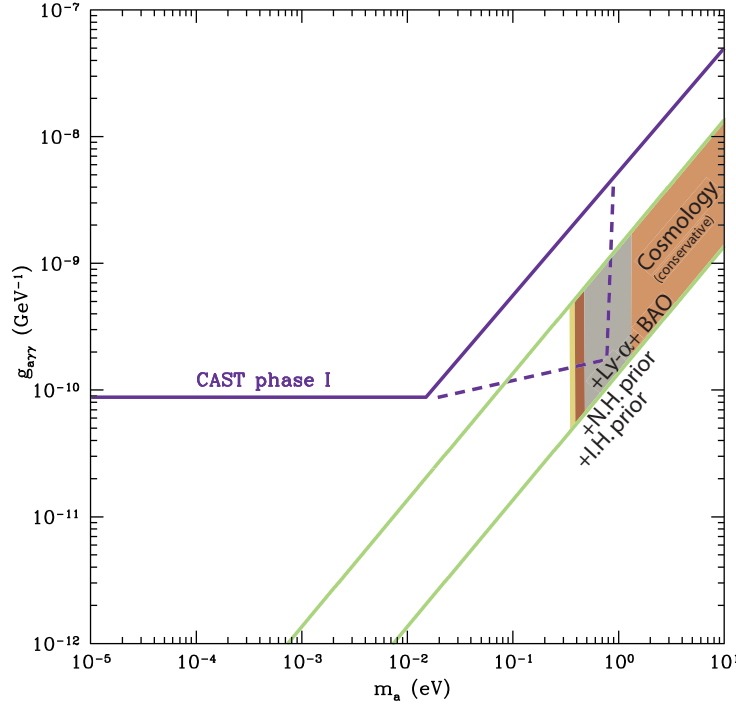


Figure 1.4: 95% CL axion mass limits in the $m_a - g_{a\gamma\gamma}$ plane for WMAP and CMB data. The bounds are confined within the region allowed by the KSVZ and DFSZ models. Three possible scenarios were considered, according to neutrino oscillation data, normal hierarchy $\sum m_\nu \gtrsim \sqrt{|\Delta m_{13}^2|} \gtrsim 0.05$ eV, inverted hierarchy $\sum m_\nu \gtrsim 2\sqrt{|\Delta m_{13}^2|} \gtrsim 0.1$ eV, and the massless neutrino case. The constraints for the axion mass for the three possible scenarios are:

$$m_a < \begin{cases} 0.34 \text{ eV,} & \text{normal hierarchy;} \\ 0.31 \text{ eV,} & \text{inverted hierarchy;} \\ 0.34 \text{ eV,} & \text{massless neutrino.} \end{cases}$$

The CAST phase I experimental bound is also reported (solid line), along with the possible reach of CAST phase II (dashed line). Figure taken from [19].

1.4.2 Astrophysical bounds

The evolution of stars, as in the case of the Universe, is also affected by the presence/absence of axions. The most significant interaction process in the stellar core is the coupling of axion to two photons (Primakoff effect), a mechanism by which stars lose energy. Consider low-mass ($0.5M_\odot$) stars in a globular cluster^(g) which ignite helium in their core, to produce carbon and oxygen. The mean energy released is 80 erg/(s·g)[16]. The production of axions inside the stellar core by the interaction of photons with the virtual photons of the electric or magnetic field of the nucleus (see fig.1.7) releases a total energy of $g_{10}^2 \times 30$ erg/(s·g), where g_{10} is the coupling constant in units of 10^{10}GeV .

^(g)A globular cluster is a group of stars formed at the same time which differ only for their mass.

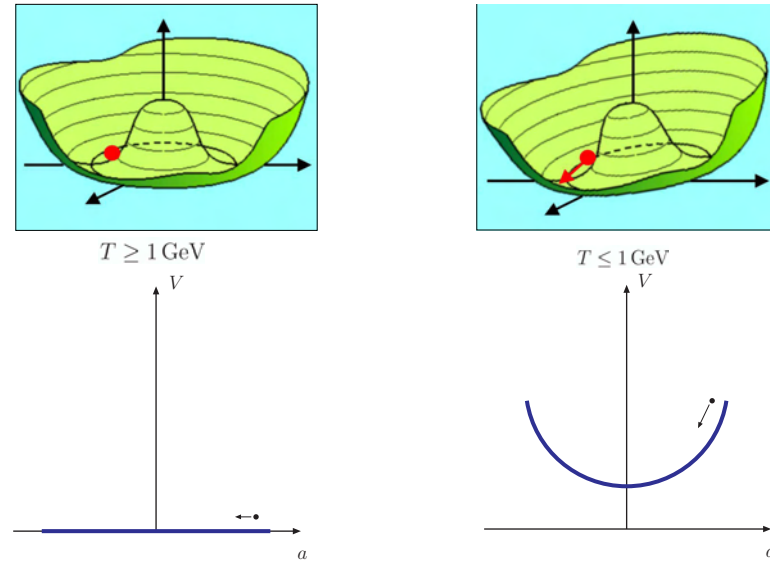


Figure 1.5: Evolution of the axion field potential before (at left) and after (at right) the QCD freeze out. The roll of the axion field is represented at right. Figure taken from ref.[20].

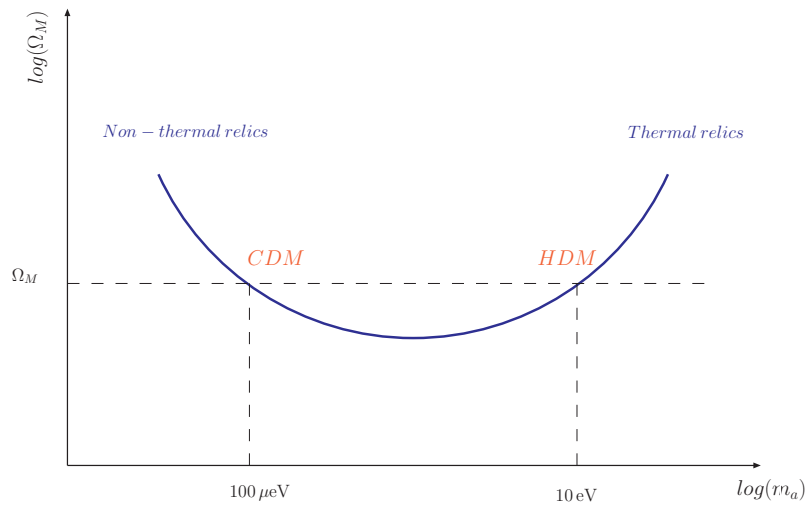


Figure 1.6: Representation of the Cold Dark Matter and Hot Dark Matter axion contribution to Ω_M , the total matter relative density, as a function of the axion mass. Figure taken from ref.[14].



Figure 1.7: The Feynman diagrams for axion interactions inside the stellar core. *Left:* the Primakoff process with photons in the electric nucleon field. *Right:* the interaction process with electrons. Figures taken from ref.[15].

The consequence is a faster burning of helium and a shorter life of the star by a factor $80/(80+30g_{10}^2)$. The stellar lifetime is deduced from the ratio between the number of Horizontal Branch (HB)^(h) stars and the number of low-mass red giants, for which the loss of energy via the Primakoff effect is negligible, in a globular cluster. The ratio agrees within 20% with expectation. This difference could be used to set the limit $g_{a\gamma\gamma} \leq 10^{-10}\text{GeV}^{-1}$ and $m_a \lesssim 30$ keV. Another constraint on axion interactions is obtained from the delay of helium ignition in low-mass red giants due to an excess of axion emission via the process:

$$e + Ze \rightarrow Ze + e + a \quad (1.30)$$

which decreases the red giant temperature and gives the bound $g_{a\gamma\gamma} \cos^2 \beta \leq 1.2 \cdot 10^{-12} \text{GeV}^{-1}$ considering a DFSZ model.

Similar constraints are obtained from neutrino signals from supernova SN1987A. Several observation showed that the burst duration was not significantly shortened by this new energy-loss channel. Numerical simulations showed that the energy loss in supernovae of that kind should be around $1 \cdot 10^{19} \text{erg/s} \cdot \text{g}$ [15]. This number could be translated into a limit on axion-nucleon coupling since axion-electron interaction is negligible. Using $C_p = 0.4$ and $C_n = 0$ (see eq.1.22) for a temperature of 30 MeV one obtains $f_a \gtrsim 4 \cdot 10^8 \text{GeV}$ and $m_a \lesssim 16 \text{meV}$ [21, 22].

^(h)HB is a stage of stellar evolution, for stars with masses near the solar one, which immediately follows the red giant branch. Stars of this kind are powered by helium fusion in the core and by hydrogen fusion in a shell surrounding the core. These stars lie along a roughly horizontal line in a color-magnitude diagram.

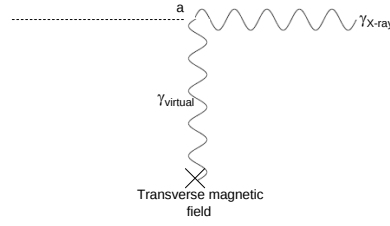


Figure 1.8: Inverted Primakoff effect.

1.5 Experimental ALP searches

In the previous section emerged that axions are not only important from a theoretical point of view, as a solution for the strong "CP problem", but have also implications in the evolution of the Universe and can be a dark matter candidate. As pointed out in the introduction, the energy scale involved in the interaction of these weakly interacting light particles is very high and out of range for the present accelerators. The only chance, at the moment, to search for WISPs is given by precision laboratory experiments. In this scenario, the preferred process to search for axions, or more generally for ALPs, is their interaction with two photons (Primakoff process). By the inversion of this process, in fact, "invisible" ALPs can be reconverted into photons. This is the revolutionary idea by Pierre Sikivie[22, 23, 24], since photons can be usually detected with "standard" technology.

The present experimental scenario for ALP searches can be divided in two classes, depending on the ALP source:

- *Laboratory experiments* where ALPs could be produced via the interaction of a laser beam with the virtual photons of an external magnetic field.
- *Astrophysical experiments* where ALPs are produced by astrophysical or cosmological sources.

1.5.1 Probability of pseudoscalar ALP conversion

In section 1.5 it was pointed out that the "invisible" ALPs flux, produced, for instance, in the stellar plasma, could be reconverted into photons[24]. It is thus very important to understand which is the probability that a stellar pseudoscalar ALP is reconverted into a photon.

The interaction of ALPs with an electromagnetic wave is described by the Lagrangian of equation 1.18. From it is clear that in a classical electrical or magnetic field an ALP conversion into photons could be induced (fig.1.8). From equation 1.18, it can also be seen that only photons with the electric field parallel to the external magnetic field are

important⁽ⁱ⁾. Applying the formalism used for the neutrino oscillations, the axion-photon oscillation is expressed through the relation[16]:

$$(\square + m_a^2)a = g_{a\gamma}\vec{E} \cdot \vec{B} \quad (1.31)$$

or, using matrices and assuming a magnetic field along the z direction:

$$\left[\omega^2 + \partial_z^2 + 2\omega^2 \begin{pmatrix} n_{\parallel} - 1 & g_{a\gamma}B_z/2\omega \\ g_{a\gamma}B_z/2\omega & -m_a^2/2\omega^2 \end{pmatrix} \right] \begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} = 0 \quad (1.32)$$

In analogy with neutrino oscillations the probability that the initial axion state a becomes the final photon state $A_{\parallel}$ travelling in a magnetic field of length L is (Lorentz golden rule):

$$\begin{aligned} P_{a \rightarrow \gamma} &= \frac{2\pi}{\hbar} |\langle A_{\parallel} | H | a \rangle|^2 \rho(a) = \frac{g_{a\gamma}^2}{4} \left[e^{-\int dz \Gamma/2} \int_0^L dz B e^{i \int dz (m_{\gamma}^2 - m_a^2)/2\omega - i\Gamma/2} \right]^2 \\ &= \frac{g_{a\gamma}^2}{4} B_{\perp}^2 \frac{1}{q^2 + \Gamma^2/4} [1 + e^{-\Gamma L} - 2e^{-\Gamma L/2} \cos qL], \end{aligned} \quad (1.33)$$

where $q = \left| \frac{m_{\gamma}^2 - m_a^2}{2\omega} \right|$ is the transferred momentum between the axion and the photon, m_{γ} and Γ are the terms which take into account that there is no real vacuum condition. In a perfect vacuum condition in fact $\Gamma = 0$ (no difference in the index of refraction) and equation 1.33 simplifies to[25]:

$$P_{a \rightarrow \gamma} = \frac{g_{a\gamma}^2}{2} \frac{(BL)^2}{2} \frac{2}{(qL)^2} [1 - \cos qL]. \quad (1.34)$$

For $qL \ll 1$ (see fig.1.9) there is complete coherent interaction and a range of axion masses is defined such that:

$$q = \frac{m_a^2}{2\omega} \rightarrow m_a^2 \ll \frac{2\omega}{L}. \quad (1.35)$$

1.5.2 Experiments to search for ALPs

This section presents a short review of experiments searching for ALPs. Experiments are divided according to their principle of operation[24].

Helioscope experiments Stellar cores are sources for axions or axion like particles. If these particles are nearly massless and weakly interacting they could escape from the stellar core, such as the Sun core, and reach the Earth. Helioscopes are magnetic telescopes which look at the Sun. The high magnetic field reconverts Nambu-Goldstone bosons into photons which could be detected by different types of detectors. The magnet bores could be either in vacuum or filled with a buffer gas

⁽ⁱ⁾This is due to the fact that axions are spin-0 bosons while photons are spin-1 bosons. The oscillation can thus happen only if the external field matches the missing quantum numbers. The longitudinal magnetic field has an azimuthal symmetry and can not match particles with different spin numbers.

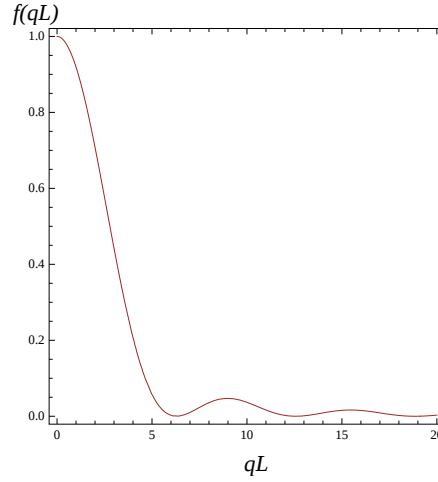


Figure 1.9: The coherence term $\frac{\sin qL}{qL}$ as a function of qL . The coherence vanishes quickly as qL increases.

to search for a different axion mass range. The CAST experiment (Cern Axion Solar Telescope)[26] and the Tokyo Axion Helioscope[27] belong to this category. The first experiment of this kind was performed by Lazarus[28] setting a limit on axion-photon coupling $g_{a\gamma\gamma} < 3.6 \cdot 10^{-9} \text{ GeV}^{-1}$ for $m_a < 0.05 \text{ eV}$ and $g_{a\gamma\gamma} < 3.4 \cdot 10^{-9} \text{ GeV}^{-1}$ for $0.086 \text{ eV} < m_a < 0.110 \text{ eV}$. The present limit of the Tokyo helioscope is $g_{a\gamma\gamma} < 6 \cdot 10^{-10} \text{ GeV}^{-1}$ for $m_a \leq 0.03 \text{ eV}$ and $(6.2 - 10.4) \cdot 10^{-10} \text{ GeV}^{-1}$ for $0.05 < m_a < 0.27 \text{ eV}$. CAST gives $g_{a\gamma\gamma} < 8.8 \cdot 10^{-9} \text{ GeV}^{-1}$ for $m_a < 0.02 \text{ eV}$ with the magnet bore in vacuum.

Crystal search The DAMA (DARK MATter) experiment[29] could be sensitive to the electric field of the NaI(Tl) crystal structure converting axions into photons. They are then detected by the crystal itself. The present limit is $g_{a\gamma\gamma} < 1.7 \cdot 10^{-9} \text{ GeV}^{-1}$ in the eV axion mass range.

Shining light through a wall experiments Axions or ALPs are produced in the laboratory by the interaction of photons from a polarized laser beam with the virtual photons of a high magnetic field. The initial photon beam is then blocked by a "wall" which is permeable to the weakly interacting ALPs. Another magnet is placed after the wall inside which the ALPs flux can oscillate back to photons (see fig.1.10,[30, 31]). In 1992 Ruoso et al.[32] performed this type of experiment using a 3.7 T magnetic field and a photomultiplier tube as a photon detector. A limit of

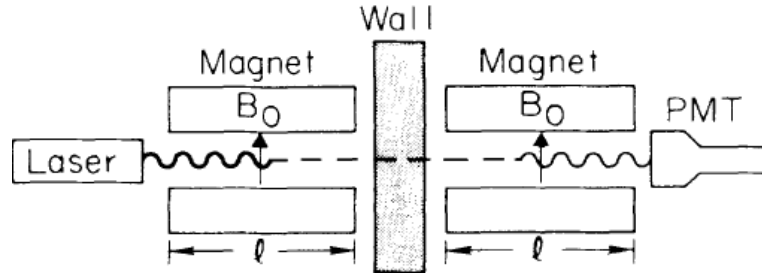


Figure 1.10: The light shining through a wall concept. Figure taken from [30].

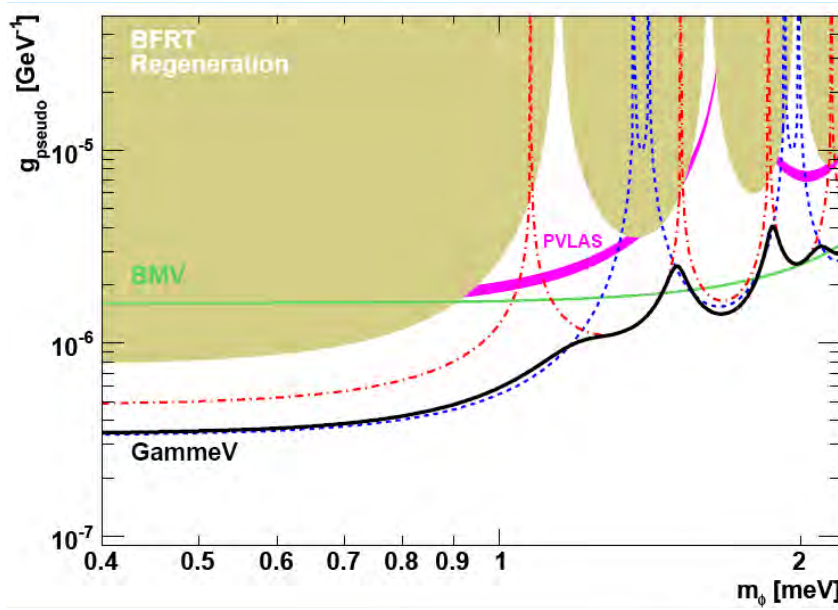


Figure 1.11: The 3σ exclusion region for the GammeV and BMV experiment are reported in the coupling constant–axion mass plot. Figure taken from ref.[34].

$7.7 \cdot 10^{-7} \text{ GeV}^{-1}$ was put on $g_{a\gamma\gamma}$ for $m_a \leq 10^{-3} \text{ eV}$.

More recently, the BMV collaboration applied this technique to search for axion like particles using a 0.25 m long pulsed magnet capable of giving $28 \text{ T}^2\text{m}$. The particular shape of the magnet coil ("X coil") enables one to have a high magnetic field in a small region[33]. This pulsed magnet was combined with a gated CCD detector in order to exploit the timing structure and lower the noise background. Along this line, the GammeV experiment at Fermilab[34] also uses a single magnet divided in two parts by a moveable septum. Moving the septum allows one to widen the range of axion masses to be scanned since the path length in the first or second magnet affects the production (reconversion) probability (fig.1.11). Other current experiments which apply similar techniques are ALPS at Desy[35] and OSQAR[36] at Cern, which uses two LHC dipole magnets. At present, ALPS is the sole ex-

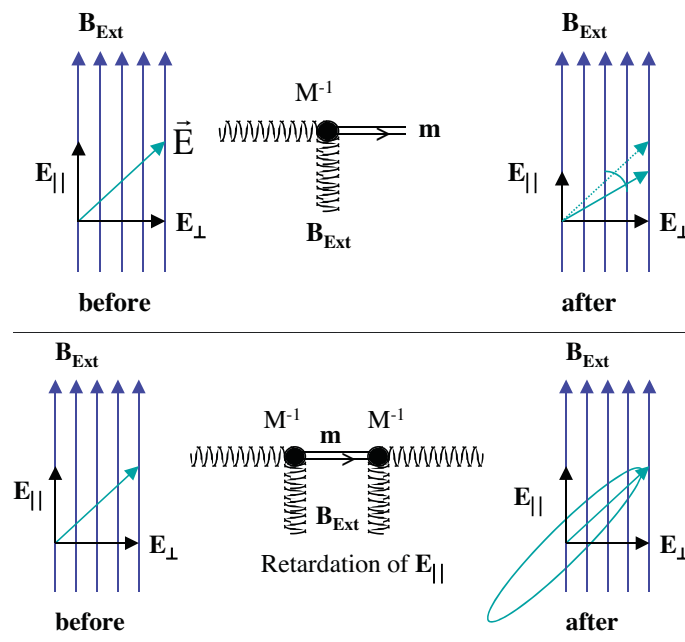


Figure 1.12: Principle of the polarization experiment to search for ALPs. Figure taken from ref.[38].

periment using a resonant Fabry-Perot cavity to increase the axion-photon conversion probability. The probability is increased by a factor equal to the Finesse of the Fabry-Perot, which can be several thousand.

Polarization experiments Another way to search for axions, or more generally for axion like particles, is based on laboratory laser production. From Quantum Electrodynamics (QED) it is known that a linearly polarized light beam crossing a vacuum region, perturbed by an external magnetic field, will change its polarization state, becoming elliptically polarized. This is due to the interaction of the laser beam with the e^+e^- loops which are present in the perturbed vacuum. This phenomenon is called the magnetic birefringence of the vacuum[37]. If one takes into account the possible existence of ALPs the contribution to this effect is not only due to QED processes but also to photons polarized parallel with respect to magnetic field, oscillating into axions via the Primakoff effect (see fig.1.12). When there is the production of a *real* particle, an apparent rotation of the polarization plane (dichroism) is induced, while the production of a *virtual* particle causes a delay of one polarization components with respect to the other, linearly polarized light becomes elliptically polarized. Experiments such as PVLAS (Polarization of Vacuum with LASer)[38, 39], PVLAS Phase II[40], Q&A[41] and OSQAR[36] experiments belong to this category. For axion masses $m_a \leq 0.5$ meV the general bound on axion-photon coupling from laser experiments is $g_{a\gamma\gamma} \leq 3.6 \cdot 10^{-7} \text{ GeV}^{-1}$.

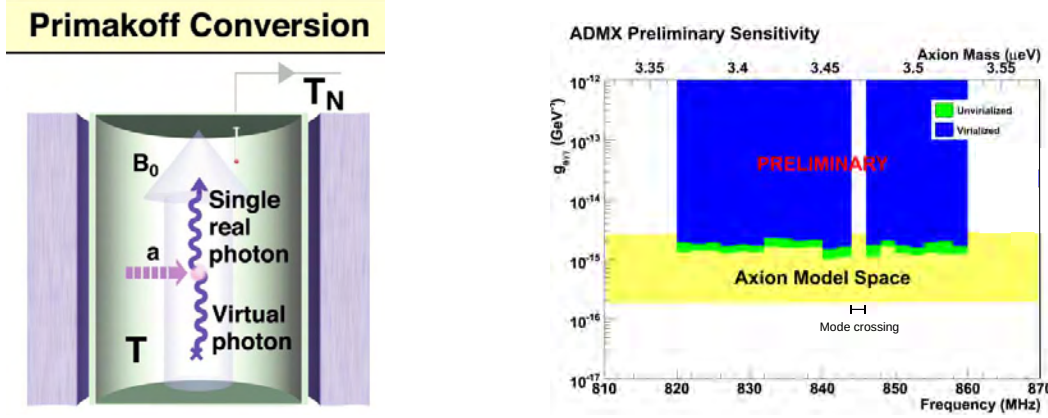


Figure 1.13: *Left:* the schematic principle of the ADMX experiment. *Right:* the bound obtained until now. Figure taken from ref.[43].

Radio source experiments-Halosopes Experiments of this type[42] are based on the idea that Nambu-Goldstone bosons were produced at a certain time of the expansion of the Universe when $\Gamma \lesssim H$, where Γ is the axion lifetime. The subsequent decoupling of these particles occurred independently in different regions of the Universe, and, if there was no inflation, different regions maintained different potential minima of the boson field. This scenario applies to axion only if they are massless. The different regions of the Universe form a gradient of the boson field and a radio signal emitted from a distant source will behave as travelling through an inhomogeneous optical medium. A linearly polarized light, for instance, will change its polarization state. This effect is independent from the wavelength. A limit on $C_{a\gamma}$ (see eq.1.19) of 10^5 can be set by the non-observation of this effect[15].

Relic dark matter searches Depending on the value of the axion scale f_a , in the early Universe, there could have been the production of thermal axions (HDM) or of cold axions (CDM). The thermal production is ruled out by experiments since it is based on a mechanism in which axions can interact only with two photons, implying an axion mass of the order of few keV. With such masses ALPs are unstable and decay immediately into photons. Low mass cold ALPs, with a mass range of 4-150 μeV can, on the other hand, be originated by the vacuum misalignment mechanism. Non relativistics cold ALPs, relics of primordial production, should therefore be found accreted around gravitational bodies. The ADMX (Axion Dark Matter eXperiment)[43] searches for axions having accumulated in the galactic halo. Axions from this halo could be reconverted into microwave photons using a high magnetic field. In the actual experiment an high Q microwave cavity is used to enhance axion-photon conversion probability. An energy excess in the cavity corresponds to an axion having a mass determined by the cavity resonant frequency.

The mass range $1.97 - 2.17 \mu\text{eV}$ was scanned by ADMX (fig.1.13) and the sensitivity in the coupling was such that the experiment has been able to actually probe a portion of the region in the axion parameter space predicted by the models.

Other sources of axions From equation 1.18 one can deduce that axions could be produced in the inhomogeneous magnetic field of certain stars, such as neutron stars ($B \simeq 10^{12} - 10^{11}$ Gauss), or white dwarf stars. At a temperature of the order of 50 keV γ -rays could be converted into axions in the magnetosphere of the star. Despite the large magnetic field the photon-axion conversion probability is very small. The photon-axion oscillation mean free path is in fact very small compared to the length of the region, thus multiple oscillations can occur, cancelling each other. To enhance, on the contrary, the oscillation, the linear dimensions of the magnetosphere must equal l_{osc} . This is obtained in magnetic white dwarf with $B = 10^9$ Gauss, $L_B = 10^3$ km and $E_\gamma = 10$ eV[15].

Summary

The present experimental bounds to ALP mass and coupling constant to two photons are summarized in fig.1.14:

1. Haloscope experiments searching for cold dark matter ALPs.
2. Helioscope experiments observing the Sun as an ALP source.
3. Telescope observations searching for thermal ALPs.
4. Laser experiments attempting ALP production and detection in the laboratory with polarization measurements.
5. Light shining through a wall experiments where ALPs are produced and then re-converted into photons using a high magnetic field.
6. Limits based on helium-burning stars evolution and luminosity.
7. Bounds based on the axion flux produced in supernovae core which should increase supernovae luminosity (conversion to γ -rays).

1.6 Solar axions

Helioscope experiments[26] consider the Sun as a furnace where axions or ALPs are produced: blackbody photons inside the solar core are converted into ALPs via the Primakoff effect. The necessary external field could be either the solar magnetic field or the electric field of the charged particles in the hot plasma. Equation 1.34 gives the

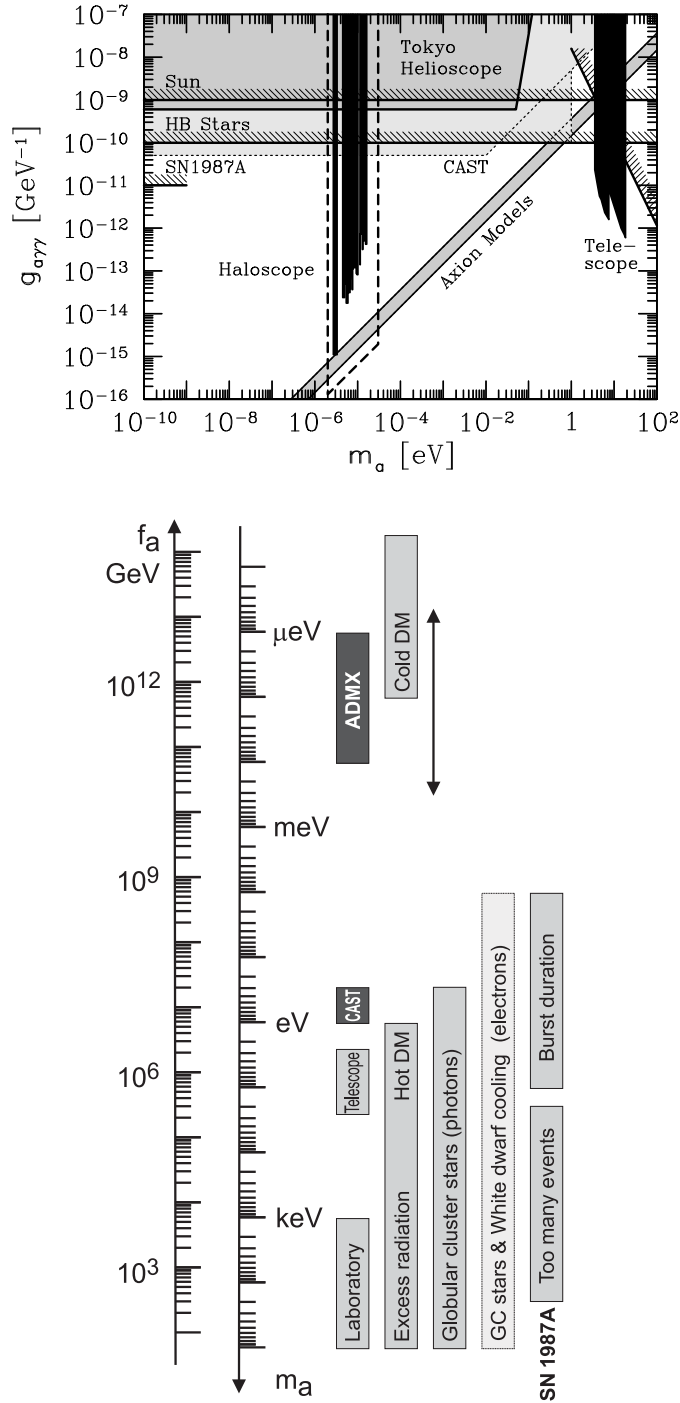


Figure 1.14: *Upper plot:* exclusion region in the mass-coupling plane for axions and ALPs from experimental searches (see text). Figure taken from ref.[23]. *Lower plot:* open windows for the “standard QCD axions”. Figure taken from ref.[16]. Limits on coupling strengths are translated into limits on m_a and f_a using $z = 0.56$ (KSVZ model, see eq.1.13). The laboratory bar is an approximate representation of the exclusion range for both standard axions or ALPs obtained from laboratory experiments. The globular cluster stars and white-dwarf cooling range uses the DFSZ model with $\cos^2 \beta = 1.2$. The Cold Dark Matter exclusion range uses the misalignment mechanism (see text).

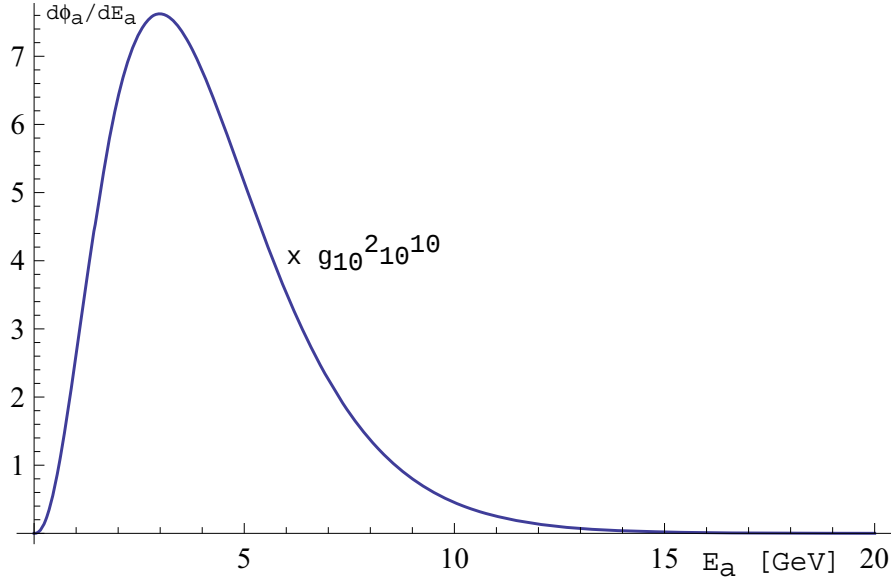


Figure 1.15: Differential axion flux reaching the Earth when a blackbody distribution for solar photons is assumed.

probability that a photon is converted into an axion in the presence of a magnetic field. Substituting the solar parameters for the core temperature ($T = 4.5 \cdot 10^6$ keV), for the core radius ($R_{core} = 20\%T_{\odot}$) and for the electron density ($\rho_e = 1.5 \cdot 10^5$ kg/m³) the Debye radius becomes:

$$\kappa = \sqrt{\frac{4\pi\alpha}{T} \sum_{i=1}^N \frac{Z_i^2}{V}} = 9 \text{ keV}. \quad (1.36)$$

Substituting these values in the equation for the solar energy loss due to axion-photon interaction (see [16]), one obtains the axion luminosity in terms of the solar luminosity $L_{\odot} = 3.827 \cdot 10^{26}$ W

$$L_a = g_{10}^2 \cdot 1.7 \cdot 10^{-3} L_{\odot}, \quad (1.37)$$

where g_{10} is the axion-photon coupling constant in units of 10^{10} GeV⁽ⁱ⁾. From equation 1.37 it is evident that if axion could escape from the Sun, this should increase its luminosity and shrink its radius.

The differential axion flux reaching the Earth, assuming a blackbody distribution for solar photons, is[15]

$$\frac{d\phi_a}{dE_a} = g_{10}^2 \cdot 6.02 \cdot 10^{10} \cdot E_a^{2.481} e^{-E_a/1.205} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \quad (1.38)$$

and is plotted in fig.1.15. The distribution is peaked at 3.0 keV, in the soft X-ray range. The mean axions flux on the Earth is obtained by integrating over the mean axion energy,

⁽ⁱ⁾The observation of the lifetime of HB stars sets a limit on $g_{a\gamma\gamma} \lesssim 10^{10}$ GeV. It is then possible to use g_{10} in calculations of axion properties.

$$\langle E_a \rangle = 4.2 \text{ keV},$$

$$\phi_a = g_{10}^2 3.74 \cdot 10^{11} \text{ cm}^{-2} \text{ s}^{-1}. \quad (1.39)$$

The solar axion luminosity could be used to bound $g_{a\gamma\gamma}$ by considering the present solar age (half of the expected lifetime of the Sun). Assuming $L_a < L_\odot$ then $g_{a\gamma\gamma} < 2.4 \cdot 10^{-9} \text{ GeV}^{-1}$.

Invisible solar axions could be reconverted into detectable X-rays using a high magnetic field on Earth (helioscope principle). In addition, axion reversion could be enhanced by choosing the right Γ (photon attenuation coefficient) which means treating photons as massive particles. This has the consequence of changing the transferred momentum:

$$q = \left| \frac{m_a^2 - m_\gamma^2}{2E_a} \right|. \quad (1.40)$$

This could be done by filling the magnet bore with a proper gas which will change the plasma frequency according to:

$$m_\gamma c^2 = \omega_{pl}^2 = \sqrt{\frac{4\pi\alpha}{m_e}} \hbar c \sqrt{n_e} = a \sqrt{n_e} = 28.9 \sqrt{\frac{Z}{A} \rho} [\text{eV}] \quad (1.41)$$

where m_γ is the "mass" of the photons, m_e is the electron mass, and n_e is the electron number density. If one uses ^4He , for instance, then

$$m_\gamma = \sqrt{0.02 \frac{p[\text{mbar}]}{T[\text{K}]}} \text{ eV}. \quad (1.42)$$

Using the relation $PV = n_e RT \rightarrow \sqrt{n_e} = \sqrt{\frac{pV}{RT}} = 1.211 \cdot 10^{11} \sqrt{\frac{p}{T}} \text{ cm}^{-3}$ (see eq.1.41). If the condition $\frac{qL}{\pi} \ll 1$ is satisfied, then

$$\begin{aligned} \frac{m_a^2 - m_\gamma^2}{2E_a} \frac{L}{\pi} &\ll 1, \\ \sqrt{m_\gamma^2 - \frac{2\pi E_a}{L}} &< m_a < \sqrt{m_\gamma^2 + \frac{2\pi E_a}{L}}, \\ \sqrt{0.02 \frac{p}{T} - \frac{2\pi E_a}{L}} &< m_a < \sqrt{0.02 \frac{p}{T} + \frac{2\pi E_a}{L}}. \end{aligned} \quad (1.43)$$

It follows that by choosing the right helium pressure a range of axion masses can be scanned to search for the mass value which will enhance axion-photon conversion. The presence of a gas inside the magnet will however cause absorption of the produced photons, and this can be taken into account in the axion-photon conversion probability by the attenuation coefficient:

$$\Gamma = \rho \mu(E_a) \frac{T}{p} \frac{P_{He}}{T_{He}} \cdot 10^6 \text{ m}^{-1}. \quad (1.44)$$

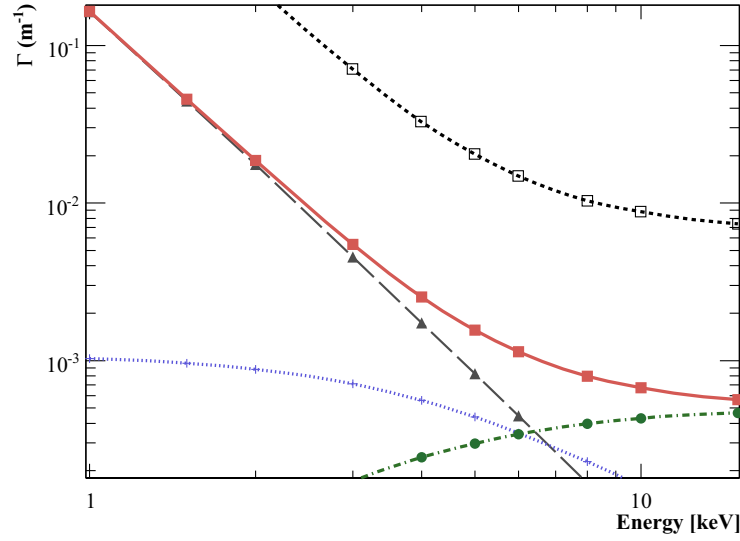


Figure 1.16: Photon attenuation coefficient for 1 mbar of helium pressure at the temperature of 1.8 K. At low energy, the main contribution is from photoelectric effect (grey triangles). At energies above 4 keV the main contribution is from incoherent scattering of photons (green circles). In black (hallow squares) the total damping suffered by photons at an helium pressure of 13 mbar. Figure taken from ref.[14].

Γ is plotted as a function of axion energy in fig.1.16.

Putting all these considerations together the expected number of photons, assuming 100% detector efficiency, is given by:

$$N_\gamma = \int P_{a \rightarrow \gamma} \frac{d\phi_a}{dE_a} \cdot S \cdot t \cdot dE_a \quad (1.45)$$

where t is the total exposure time and S the effective reconversion area (the magnet bore area in case of helioscope experiments). Recalling the expression for $P_{a \rightarrow \gamma}$ (see eq.1.33), then

$$N_\gamma = \int g_{10}^4 \frac{B^2}{4} \frac{1}{q^2 + \Gamma^2/4} [1 + e^{-\Gamma L} - 2e^{-\Gamma L/2} \cos qL] \times 6.020 \cdot 10^{10} E_a^{2.481} e^{-E_a/1.205} S t dE_a. \quad (1.46)$$

In the case of pure vacuum the previous formula becomes:

$$\begin{aligned} N_\gamma &= g_{10}^4 \frac{B^2 L^2}{4} \frac{2}{q^2 L^2} [1 - \cos qL] S t \int 6.020 \cdot 10^{10} E_a^{2.481} e^{-E_a/1.205} dE_a \\ &= g_{10}^4 \left(\frac{BL}{2} \right)^2 \frac{4}{q^2 L^2} \sin^2 \frac{qL}{2} S t \int \frac{d\phi_a}{dE_a} \cdot dE_a \\ &= g_{10}^4 \left(\frac{BL}{2} \right)^2 \left[\frac{2}{qL} \sin \frac{qL}{2} \right]^2 \int \frac{d\phi_a}{dE_a} \cdot dE_a S t. \end{aligned} \quad (1.47)$$

1.7 Solar corona problem and low-energy photons

The spectrum of reconverted photons from solar ALPs is expected to be peaked at 3.0 keV. Nevertheless, the mechanism for the production of solar ALPs is not fully understood and there might be some process in the Sun which will enhance both the low and high energy tails of the spectrum of figure 1.15. Low energy ALP production could be, for instance, related to the solar corona problem or to the presence of spots with high magnetic fields on the solar surface. An high energy tail could be related to 14.4 keV axions emitted from the Sun in an M1 nuclear transition between the first, thermally excited state, and the ground state of the ^{57}Fe nuclide. ^{57}Fe can be a suitable axion emitter due to its first excitation energy of 14.4 keV, which is low enough to be thermally excited in the hot solar interior, and to its exceptional abundance among the heavy elements in the Sun. This section is focussed on processes which could enhance the low energy tail of the spectrum (low-energy photons). For a description of the high-energy tail enhancement see ref.[44].

The solar corona problem is one of the most puzzling features of the Sun. The Sun is composed of different layers: the core, the photosphere, the chromosphere and the corona. The corona extends for more than 10^3 kilometers from the solar surface and its temperature is very high, reaching $2 \cdot 10^6$ degrees. It is the region where the solar wind has its origin. There are three types of mechanisms by which solar photons can interact with the plasma of the corona:

1. free electron scattering,
2. scattering on dust particles,
3. emission spectrum from ions in the solar coronal plasma.

One of the things that is least understood of the corona is its temperature[45], which is at least 200 times higher than the solar surface, and the mechanism which allows the corona to exist at all. Furthermore, the solar corona is not homogeneously distributed around the chromosphere during the entire solar period. When the Sun is quiet, the corona is present mostly around the equatorial region, leaving holes at the poles, while during active Sun periods it is evenly distributed over the equatorial and polar regions and it is more prominent in regions corresponding to sunspots activities. The so called coronal loops, loops of magnetic flux from the solar core (fig.1.17), originate in these places.

There are presently two theories attempting to explain the solar corona heating (a combination of the two actually appears as the most plausible):

1. wave heating,
2. magnetic reconnection.

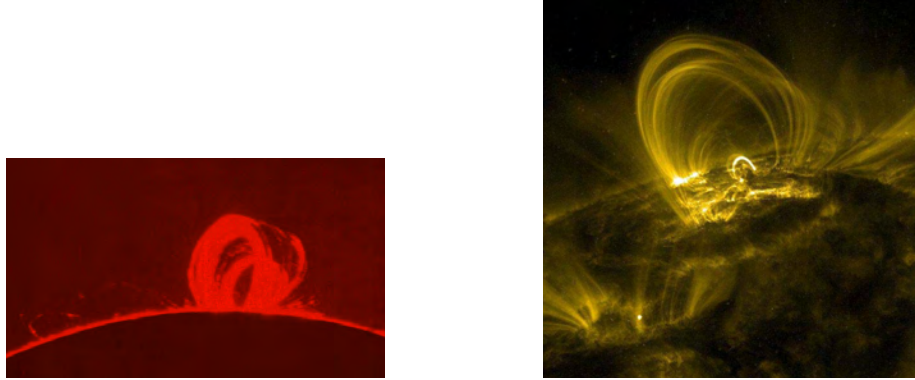


Figure 1.17: Images from the solar coronal loops from the solar interior. Figures taken from [46] and Wikipedia.

To these one should add the possibility that corona heating is related to ALP production.

The wave heating theory was proposed in 1948[47] and tries to explain the hot corona using wave heating from the solar interior. In the core plasma there could be the formation of magneto-acoustic waves and Alfvén waves, which are sound waves modified by the presence of a magnetic field, and ULF radio waves modified by the interaction with plasma matter, respectively. The energy required to heat up the corona is 1 kW/m^2 which means $\frac{1}{4 \cdot 10^4}$ of the total energy released from the Sun. After travelling in the solar interior these waves became shock waves near the transition region, transferring their energy to the solar corona and consequently heating it. This scheme, however, does not solve the entire problem, since it is not understood how the heat is actually transferred to the correct region. Magneto-acoustic waves in fact are blocked or reflected back in the chromosphere, and thus can not reach the solar corona. Alfvén waves, on the other hand, could reach the corona, but dissipate energy too slowly to explain the coronal temperature. Magneto-acoustic waves were actually observed in the solar corona, but as random waves they could not explain the uniform temperature of it.

The magnetic reconnection theory is based on the principle that the magnetic solar field creates currents loops in the solar corona. Is is a known fact from electromagnetism that two magnetic field lines can not have points in common. When two magnetic filaments become so near that they could cross each other, they break losing their energy in the solar corona and then reconnect in different way. The energy released is in the form of UV photons.

The ALP production solution is related to the presence of a magnetic field near the surface of the Sun[48, 49, 50]. ALPs created in the interior of the Sun by X-ray photon conversion could be again reconverted into X-rays which will then heat up the solar

corona. This view, however, appears to be contradicted by the distribution of X-rays reaching the Earth. Such photons should have a blackbody distribution when they arrive to the Earth, but in reality present a power law spectrum, and also seem not to be emitted radially. This behaviour could be explained by looking at the solar corona plasma ionization. Ions could in fact emit free electrons which will scatter the X-rays, lowering their energy, giving rise to a power law spectrum, and also changing their angular distribution. MonteCarlo simulations show that this mechanism is possible if axions with $m_a \lesssim 0.02$ eV are taken into account. This would be the "cold" dark matter axion, explaining also the strong CP problem.

It is also possible that part of the visible solar luminosity near the sunspots is decreased due to photon conversion into ALPs. This phenomenon would enhance the low energy tail of the reconverted photon spectrum. In this scenario the solution for the solar corona problem is the axion-photon oscillation. The solar photosphere is getting colder because part of its visible photons escape into axion form, while the corona becomes hotter because axions generated in the solar core from X-ray photons are reconverted back by the surface magnetic field.

Moreover low energy axion production could be enhanced by the presence of intrinsic solar magnetic fields. This enhancement takes place when the local plasma frequency, ω_{pl} , fits the axion rest mass. The maximum coherence length can then be equal to the photon mean free path length (a few centimeters in the solar core, 100 km near the Sun surface) providing a quasi resonant condition

$$\hbar\omega_{pl} \simeq m_a c^2. \quad (1.48)$$

Such a process can modify the axion energy spectrum, depending on the strength of the magnetic field. In this way a high magnetic field outside the hot core could enhance low energy axion production.

These models apply not only to the Sun, but to all the stars that as the Sun have an external corona hotter than the inner chromosphere.

Chapter 2

The CAST experiment at Cern

The CAST (Cern Axion Solar Telescope, see fig.2.1 for a view of the experimental hall) experiment at CERN searches for solar ALPs based on the helioscope principle. CAST uses an LHC prototype dipole magnet installed on top of a moving platform which allows tracking the Sun twice a day, at sunrise and at sunset. In this way, the CAST magnetic field is transverse with respect to the flux of solar ALPs, maximizing the ALP-photon conversion probability, which becomes (eq.1.34):

$$P_{a\gamma} = 2.1 \cdot 10^{-17} \left(\frac{B}{9\text{T}} \right)^2 \left(\frac{L}{10\text{m}} \right)^2 (g_{a\gamma\gamma} 10^{10} \text{GeV}^{-1})^2 |M|^2 \quad (2.1)$$

where $|M|^2 = 2(1 - \cos qL)(qL)^2$ can be taken equal to 1 as long as the coherence condition is maintained. When the magnet bore is in vacuum this happens for ALP masses less than 10^{-2} eV.

X-ray detectors are placed at each end of the magnet to acquire the reconverted photon signal. The expected number of photons reaching each detector in vacuum condition is, from eq.1.45,:

$$\frac{N_\gamma}{t} = P_{a\gamma\gamma} \cdot \Phi_a \cdot A = 7 \text{ events/day} \quad (2.2)$$

where $P_{a\gamma\gamma}$ is given in eq.1.34, Φ_a is the mean solar axion flux (eq.1.38), and $A = 14.5 \text{ cm}^2$ is the magnet bore cross section. Only X-rays from reconverted axions in the energy range 1-10 keV are considered, and the coupling is assumed $g_{a\gamma\gamma} \sim 10^{-10} \text{ GeV}^{-1}$. To maximize the ALP-photon conversion probability, the next step is to fill the magnet bore with gas (helium-4 or helium-3), which, as seen in section 1.6, has the consequence of giving a mass to photons, $m_\gamma = \omega_{pl}$, widening the ALP mass range that can be studied.

2.1 CAST apparatus

2.1.1 The LHC dipole magnet

The CAST magnet is a decommissioned LHC prototype dipole magnet (see fig.2.2),



Figure 2.1: View of the CAST (Cern Axion Solar Telescope) apparatus at Cern. The magnet is placed on a moveable platform in order to point at the Sun, maximizing the ALP-photon conversion probability (*see text*). Figure taken from the CAST website: <http://cast.web.cern.ch/CAST/index.html>

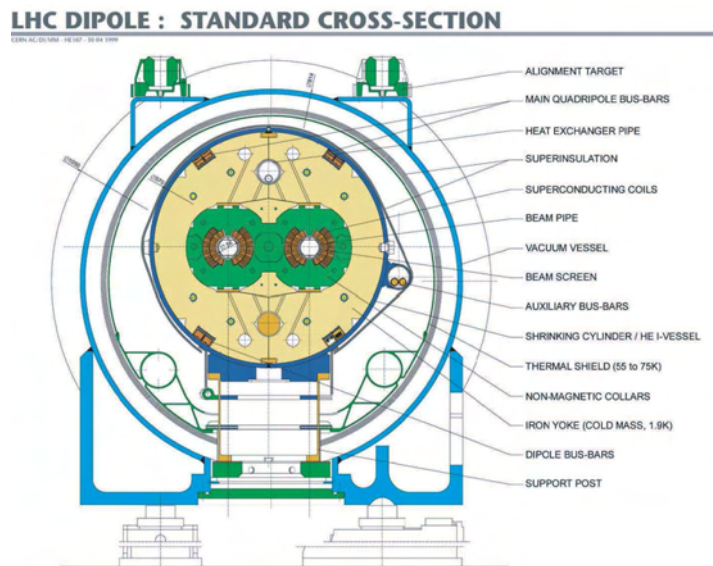


Figure 2.2: A frontal section view of the LHC prototype dipole magnet used at CAST(*see text*). Figure taken from ref.[36].

L_c [m]	E_a [keV]	m_a [eV]
10	4	0.02
0.5	4	0.10
0.02	4	0.5

Table 2.1: Coherence length $L_c = (2\pi\hbar c)E_a/(m_a^2 c^4)$ for different ALP masses. A mean energy of 4 keV for the X-ray photons is considered.

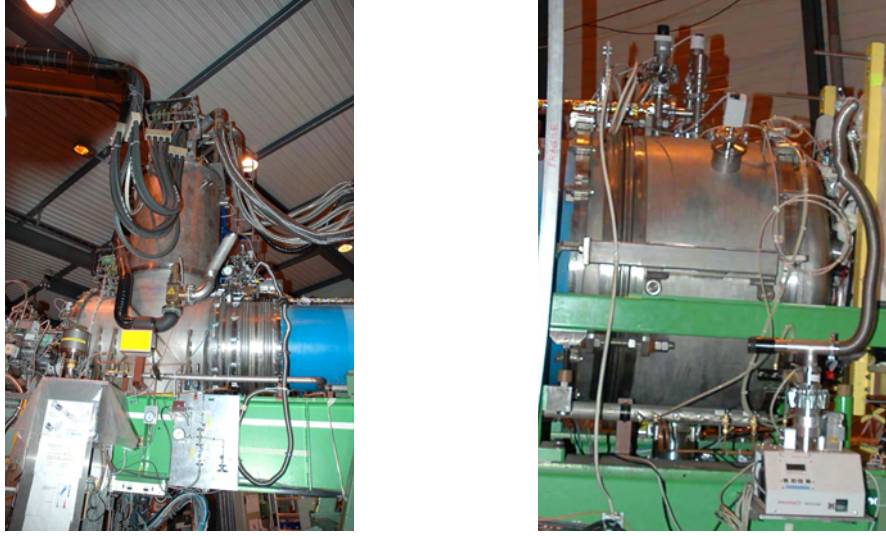


Figure 2.3: Magnet Feed Box (left) and Magnet Recovery Box (right) at the ends of the CAST magnet. The MFB contains all the cryogenics and electronics for the cooling of the magnet, while MRB is used as a helium storage box when the magnet is tilted. Figures taken from ref.[14].

with two straight bores, each with a cross section of 14.5 cm^2 , and a total magnetic field of 9.6 T over 9.5 m. The angular aperture of each bore (10 mrad) fully covers the potential source of ALPs under test, while the magnet length allows scanning masses less than 0.02 eV in pure vacuum condition (see table 2.1 for a comparison with ALP coherence lengths).

To reach this high magnetic field, corresponding to 13 kA of coil current, the magnet is cooled at 1.8 K via superfluid helium. The LHC dipole, in fact, becomes superconducting at temperatures below 4.5 K. The use of superfluid helium has the advantage of keeping the magnet cooled even if it is tilted, as it is needed for the CAST experiment to point the Sun. The maximum tilting angles are $\pm 8^\circ$ in the vertical direction and $\pm 40^\circ$ in the horizontal direction, which limit the effective data taking time to only one hour and half at sunrise and one hour and half at sunset.

The cryogenics and the electrical connections, needed to fill the magnet with superfluid helium, are contained in the Magnet Feed Box (MFB, see fig.2.3 left) placed on the



Figure 2.4: A quench in the CAST area. The tall visible at center cloud is the magnet cooling helium escaping as a gas. Figure taken from ref.[14].

sunset side of the magnet, while, at the other end, there is the Magnet Return Box (MRB, see fig.2.3 right), which contains the liquid helium when the magnet approaches its maximum tilt angles. To allow the magnet movements all feeding pipes and the current cables are made flexible.

An interesting phenomenon related to superconducting magnets is the *quench* (see fig.2.4), a sudden change from the superconducting phase to the normal-resistive phase of the magnet material caused by the presence of impurities. This sudden change creates an increase electrical resistivity which consequently will warm the magnet due to the Joule effect. Cold helium gasifies and causes an overpressure of gas in the cryostat which must be quickly evacuated in order not to damage the system.

2.1.2 Tracking System

The CAST mobile platform is shown in figure 2.5. There are two mobile areas: the pyramid-shaped support placed on the sunrise side, which is equipped with two calibrated screws which make the vertical movement possible, and the turntable placed in the middle-left of the magnet, which allows a movement of about 80 degrees in the horizontal plane, and of about 16 degrees in the vertical plane.

The platform is moved by two motors, one for the vertical and the other for the horizontal movement. Each motor is connected to an encoder so that the coordinates of the CAST magnet in the hall are recorded independently for the two directions.

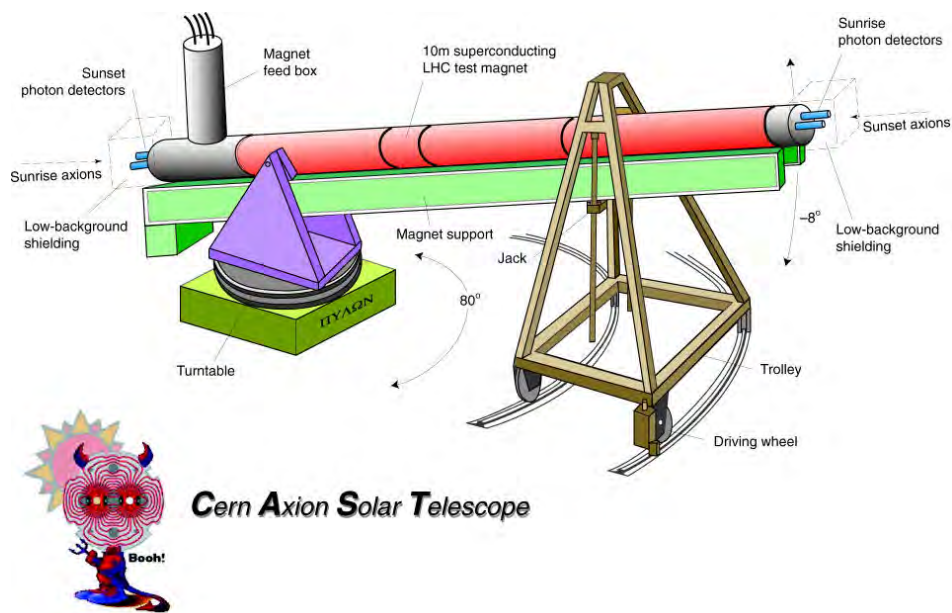


Figure 2.5: The CAST mobile platform. The two movement regions are shown. The pyramid-shaped support on the right of the figure (sunrise side) allows the vertical movement while the turntable placed in the middle-left of the magnet allows the horizontal movement. Figure taken from <http://cdsweb.cern.ch/record/5791/files/cast.jpg>.

The movement of the motors is guided by the *tracking software* which converts the coordinates (galactic) of a celestial object, such as the Sun, into encoder coordinates and checks every minute the magnet axis position with respect to the magnet final position. The accuracy in the magnet axis position is of 0.01° .

In parallel and independent of the tracking software, there is the *slow control software* which constantly monitors the various CAST parameters, such as pressure, temperature, state of valves, and alerts people if something is wrong.

2.1.3 Sun filming

Sun filming is a way to check the tracking accuracy of the CAST magnet by filming the Sun during the tracking with two CCD cameras (one belonging to the Trieste group[51] and one to the the Freiburg group[52]) aligned with the CAST magnet axis. It can be performed only twice a year, during March/April and August/September, when the Sun crosses the glass window open in the CAST hall (see fig.2.6 at left). To check the correct coordinates of the Sun the atmospheric diffraction must be taken into account, since the

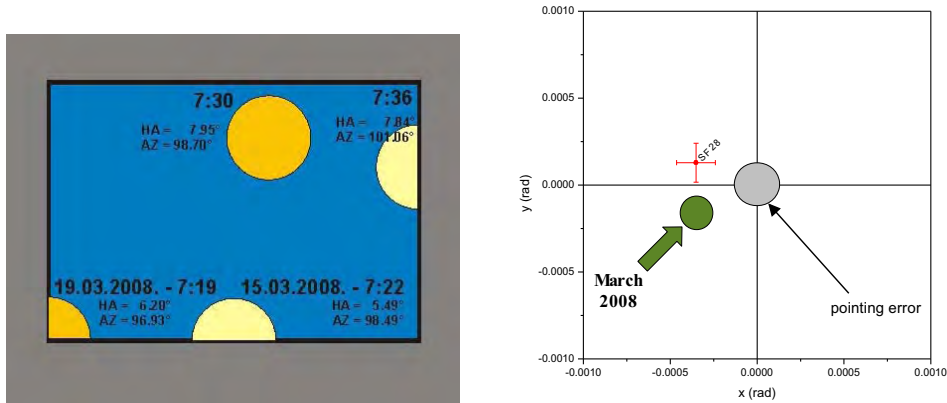


Figure 2.6: *Left:* pictorial view of the CAST hall window during sun filming. The Sun could be followed by the camera only for a maximum of 15 minutes during the sun filming. *Right:* Sun filming results. The magnet offpointing is of the order of 0.02° .

direction of the incoming light rays could be changed proportionally to:

$$R = \text{diffraction} = \theta - \theta' \quad (2.3)$$

where θ is the true zenith distance and θ' is the apparent one. The same relation is applied for the altitude angles.

The Trieste sun filming apparatus was aligned parallel to the CAST magnet axis with the help of the surveyors and placed with an error of 0.2 mm, which means that in the worst case the Sun filming axis is defined with an error of $1.7 \cdot 10^{-5}$ rad. A laser beam, also previously aligned, is used to check the magnet return to parking position after the filming.

The pictures taken during Sun filming were analyzed with a software developed in Lab-view Vision that searches for edges in a given region of a picture and then performs a circular fit through the points found. The software for the averaging procedure overlaps the pictures taken during the filming while maintaining the highest brightness value of each pixel. This will improve the determination of the center of the Sun, in particular for those days in which the Sun is partly covered by foliage or clouds.

The errors considered while determining the pointing are:

- alignment error,
- quantization error,
- error in the center determination.

The results obtained are shown in fig.2.6 at right. The origin of the coordinate system corresponds to a pixel where Sun center is expected to be. The error bar is one standard deviation. It can be seen that the magnet is slightly ahead of the Sun.

2.1.4 The Helium system

The search for axions or ALPs with the CAST apparatus can be divided in two phases.

1. Phase I: from 2003 to 2004 the experiment operated with vacuum inside the magnet bores, thus exploring the axion mass range up to 0.02 eV[53]. No excess of photons was shown during the solar tracking. The upper limit on $g_{a\gamma\gamma}$ was $8.8 \cdot 10^{-11} \text{ GeV}^{-1}$ at 95% C.L.[54].
2. Phase II: during 2005 and 2006 the magnet bore tubes were filled with ^4He gas. The range of axion masses up to 0.39 eV was scanned by filling the cold bore with a gas pressure ranging from 0 to 14 mbar. A higher pressure is not allowed since at 1.8 K helium-4 liquifies at 16.4 mbar. The measurement time at each pressure setting was only few hours, resulting in a small number of events and therefore in large statistical fluctuations. The upper limit on $g_{a\gamma\gamma}$ was $2.2 \cdot 10^{-10} \text{ GeV}^{-1}$ at 95% C.L. for $m_a < 0.4 \text{ eV}$ [26].

The next phase is to use helium-3 inside the magnet bores, since, at 1.8 K, it liquifies at a pressure of 135.6 mbar thus allowing a range of ALP masses up to 1.2 eV to be scanned, which better match the existing astrophysical constraints.

The gas system of the CAST apparatus is schematically shown in fig.2.7. The gas pressure and temperature are continuously monitored in order to inject the correct amount of gas without warming the magnet. To maintain the gas stable, prior its injection into the cold bore, it flows through a thermal bath of two liters of water (temperature 36°C) which allows an accuracy in the gas injection of 60 ppm. In order to avoid gaps between two adjacent ALP mass regions each pressure step is determined allowing a shift in the expected X-ray peak of a FWHM per step. The accuracy of the pressure step is 0.01 mbar and it is reproducible within 0.1 mbar.

In addition, damping elements are fixed all along the helium containing pipe to prevent the formation of thermo-acoustical waves which will create gas density fluctuations making the peak shift in an uncontrolled way. Another effect to account for is the density changes due to the vertical movements of the magnet, which are negligible for low ALP masses due to the small tilting angle, but which will become important as the pressure increases (as it will be for the helium-3 phase), affecting the expected number of photons firing the detectors.

An important element of the helium system is the presence of the confinement windows (see fig.2.8). These windows must be strong enough to contain the gas, must be stable and transparent to visible light to allow inspection and checking by laser beams, and obviously must have low permeability to helium and must not block X-ray photons. To

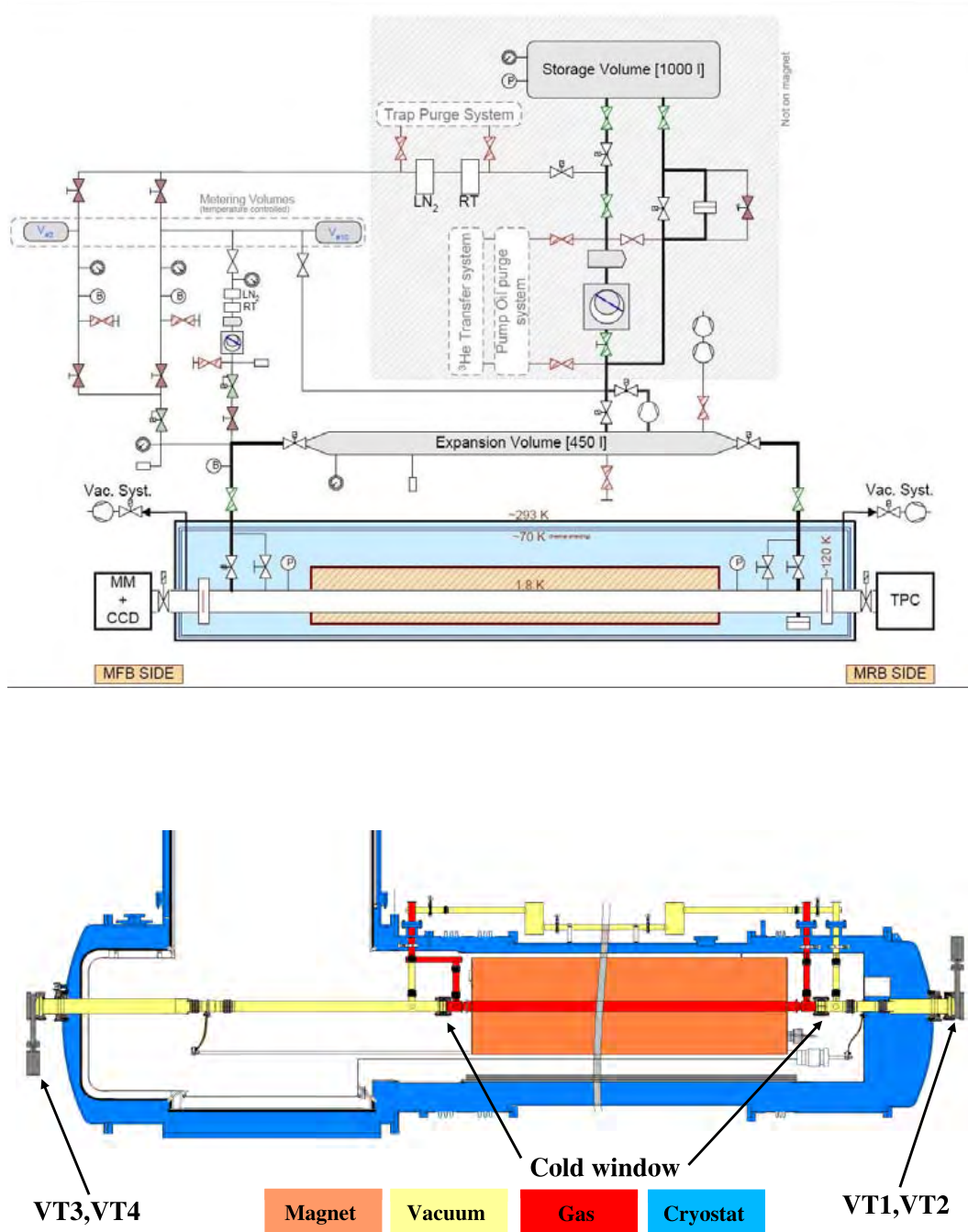


Figure 2.7: Scheme of the gas lines at the CAST experiment. In the upper picture is shown the pumping system layout and the storage volumes. In the lower picture are highlighted the different parts of the cryogenic system. The orange region is the cold region of the CAST magnet. Figure taken from ref.[14].



Figure 2.8: The helium gas system confinement window. Figure taken from [14].

match these requirements an element with low Z must be chosen, such as beryllium or plastic. The final choice was a $15\ \mu\text{m}$ thick polypropylene film with an electro-eroded grid structure (called strongback) to resist up to 150 mbar of pressure difference.

The system is also equipped with a recovery volume where the helium gas could escape in case of a quench thus avoiding damaging of the cold bore windows.

2.2 Detectors

In order to acquire the X-ray photons from the ALP reconversion detectors are placed at the both ends of the CAST magnet. The main characteristics of the sensors are:

- high quantum efficiency in the range 1–15 keV,
- low background.

The detectors presently used at CAST are three *MICROMEGAS* and one *CCD*[55, 56]. Each detector covers one bore of the magnet: two Micromegas are placed on the sunrise side (the side which takes data during sunset) and the other Micromegas plus the CCD are placed on the sunset side (the side which takes data during sunrise). In a previous setup the sunrise side was covered by a Time Projection Chamber (TPC), which looked at both magnet bores. Temporally, after the removal of the TPC detector but before the installation of the two Micromegas, a low-energy (few eV) system was used. This system consisted of a PhotoMultiplier Tube (PMT) and a Geiger-mode Avalanche PhotoDiode

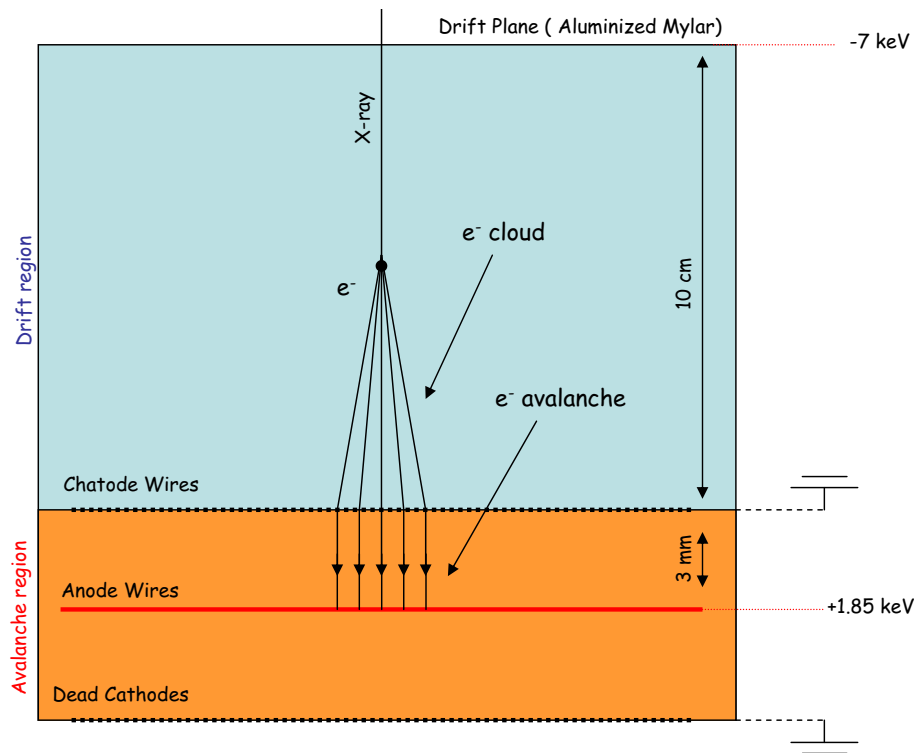


Figure 2.9: The TPC functioning principle. Figure taken from ref.[14].

(G-APD).

The picture in fig.2.5 gives an idea of the positions of the detectors. Each detector acquires data for one hour and half in the morning or in the evening, depending on its position, while the rest of the day is dedicated to calibration and background runs. In this way background data are acquired for a period ten times longer than "live" data.

A brief description of the detectors is given below.

Time Projection Chamber: was used for its robustness and the well known detection technique. The detector is a combination of a drift chamber and a multiwire proportional chamber. The central part (fig.2.9) is a mixture of gases (argon and methane at atmospheric pressure) where X-rays interact and generate electrons via ionization processes. The electrons drift, driven by the high electric field, to the anode where they produce an avalanche. The 3-D coordinates are obtained by the anode hit, the cathode hit and finally by the drift time. To reduce background, especially the one due to cosmic X-rays, a passive shielding was placed all around the detector. It consisted of a multiple layer of copper, ancient lead, cadmium and polyethylene. The whole is finally surrounded by a plastic box where nitrogen continuously flows to reduce the presence of radon near the TPC. The background count rate reached with this shielding was $(7.68 \pm 0.01) \cdot 10^{-5} \text{ counts/cm}^2 \cdot \text{s} \cdot \text{keV}$ [26]. Once a day, be-

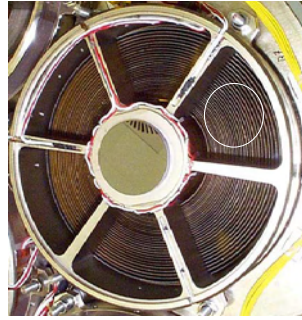
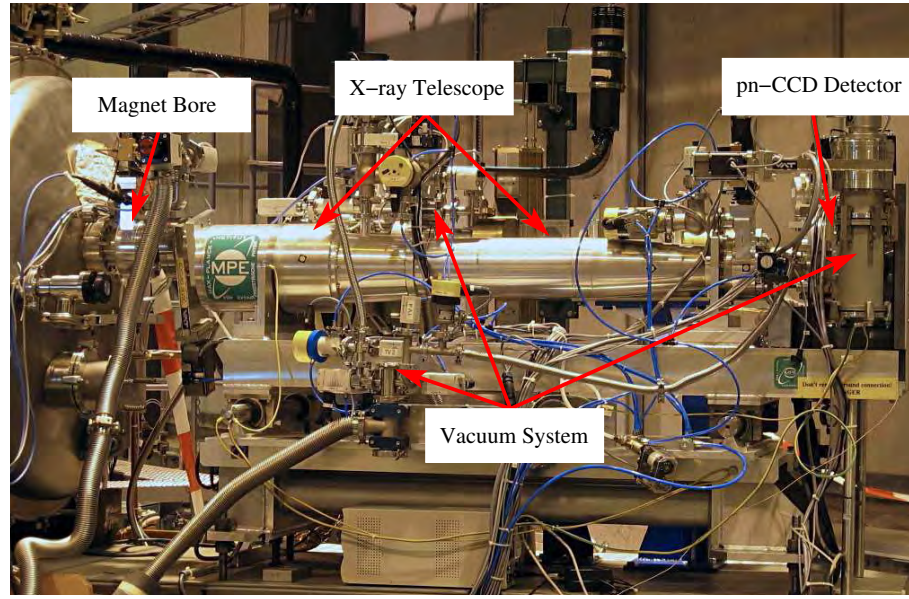


Figure 2.10: The X-ray telescope at CAST. *Top:* global view of the Wolfer I telescope. *Bottom:* picture at left shows the spider structure of the focussing optic. The pn-CCD sensor is shown at the right. Figure taken from ref.[56].

fore the run, the detector was calibrated using a ^{55}Fe source placed on the other end of the magnet[57].

CCD detector: is placed on the sunrise side of the magnet[58, 59, 56]. It is equipped with an X-ray telescope[56] in order to focus the X-rays, reconverted from axions, on the active area of the detector. The expected X-ray beam leaves, in fact, the magnet bore with a divergence due to the angular size of the axion-producing region in the Sun (from 0 to $0.2R_{\odot}$, where $R_{\odot}$ is the solar radius). The solution is to choose either a large area detector as the TPC or a focussing optic. The latter solution has the advantage of reducing background from the 14.5 cm^2 bore area to the 9.4 mm^2 CCD spot area. This area is actually smaller than the CCD active area so background and signal counts can be acquired simultaneously.

The X-ray telescope (see fig.2.10) uses the well known technique of Wolfer I mirror optics used in astronomy[60]. The telescope consists of 27 nested parabolic and hyperbolic mirror shells, made of gold and nickel, with an outer diameter of 163 mm and an inner diameter of 76 mm. All the mirror shells are placed in a spider structure which subdivides each of the 76 mirror shells into 6 sectors. Since the CAST magnet bore is smaller than the outer shell diameter, only one sector is used. The sector used is thus placed off axis. The pn-CCD detector is positioned in the focus of the telescope (total focal length of 1600 mm). It is a 280 μm thick silicon chip and has a quantum efficiency of 95% in the X-ray range. The sensitive area of the chip is 2.88 cm^2 (200x64 pixels). To reduce background, the detector is cooled to -150°C through a stirling cooler system (cold finger copper contact). To further reduce the background the detector is surrounded by a passive shielding of high purity, oxygen free copper and low-level contamination lead^(a). Every morning, after the tracking run, the pn-CCD detector is calibrated with a ^{55}Fe source. The detector background is $(8.66 \pm 0.06) \cdot 10^{-5}$ counts/ $\text{cm}^2 \cdot \text{s} \cdot \text{keV}$ [26].

Micromegas: The Micromegas detector operating principle is sketched in fig.2.11. After traveling into a vacuum region in front of the detector, photons enter the conversion drift region, which contains a mixture of Argon (95%) and Isobutane (5%), where electrons are created via the photoelectric effect. An electric field of 250 V/cm drifts electrons to the micromesh region. Here electrons generate an avalanche. The resulting electrons are collected onto X and Y strips of the anode plane. To reduce background, as for the CCD detector, a passive shielding is used. The main sources of noise are the natural radioactivity and the cosmic rays. The detector is matched to the CAST cold bore with an aluminium tube and a flange. In order to couple the gaseous detector with the vacuum or buffer gas in the magnet pipes, without affecting the X-ray flux, a differential pumping system is used. As for the other detectors every day a calibration is done using a ^{55}Fe source. The present background level of the detectors is $(4.75 \pm 0.02) \cdot 10^{-5}$ counts/ $\text{cm}^2 \cdot \text{s} \cdot \text{keV}$ [26], with a trigger rate of 0.7 Hz and a 92% efficiency[55].

Low-energy detectors: were installed temporally on the CAST experiment in 2007-2008.

The detector experimental setup is described in detail in a later chapter, here there is just a brief introduction. The detector, being sensitive in the visible range, is matched to the CAST magnet bore through a Galilean telescope and an optical fiber. The telescope serves to focus the 14.5 cm^2 cross-section of the magnet bore onto the optical fiber aperture. The fiber, 40 m long, is then used to drive the light into the detector, which is placed far away from the magnet. Before the detector system

^(a)with a very small concentration of ^{231}Pb

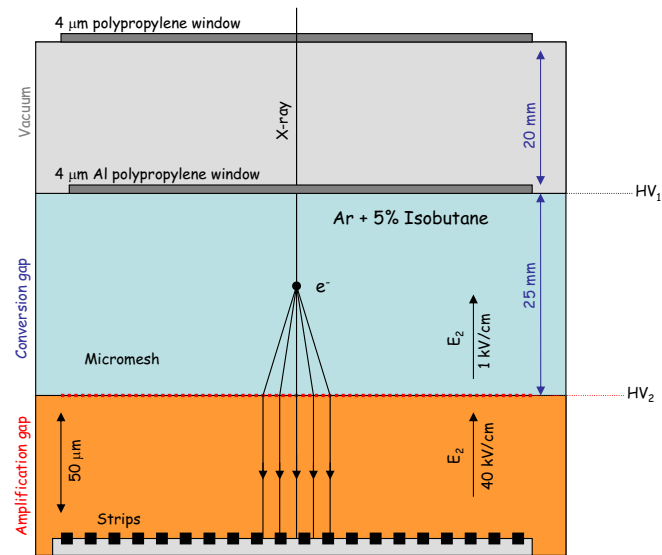
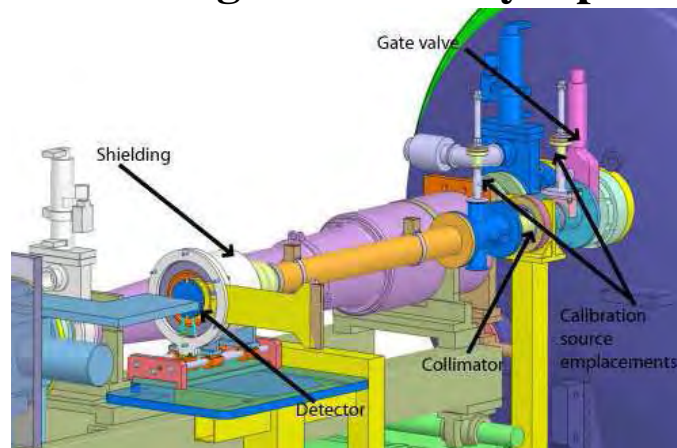


Figure 2.11: *Top:* 3D drawing of the Micromegas detector. *Bottom:* the Micromegas detector operating principle (See text). Figure taken from ref.[59].

is placed an optical switch. This device is used to share the light between two detectors and to perform light-background data acquisition simultaneously.

Chapter 3

Low background sensors for low energy photon detection

The principle of operation of the low-energy detectors used in the CAST experiment is described in this chapter. The main requirements for the detectors are sensitivity in the energy range 300-1100 nm (1-2 eV), and a low enough background making these sensors suitable for single photon counting. With a sufficiently low background, in fact, these detectors could be used in those situations where rare events are expected. This field of application includes not only the CAST experiment, but also laboratory based WISP search experiments.

The detectors characterized here are a photomultiplier tube and two types of avalanche photodiode used in Geiger mode. The principle of operation of the photomultiplier tube and the first tests are described in the first section, while the avalanche photodiodes, as an evolution of the photomultiplier tubes, are presented in the second part of the chapter.

3.1 PhotoMultiplier Tube (PMT)

A photomultiplier tube is a device which converts an optical signal, such as visible light, into an electrical one and then amplifies it. It is based on a vacuum tube with an entrance glass window and an electron multiplier chain. Its response depends only on its quantum efficiency and on its gain, that is the maximum amplification of the signal. This section describes first the principle of photoelectric emission, and then the design and operation of a PMT. The description of the electronic chain used to read the photomultiplier signal and the preliminary tests done on an actual PMT follow at the end.

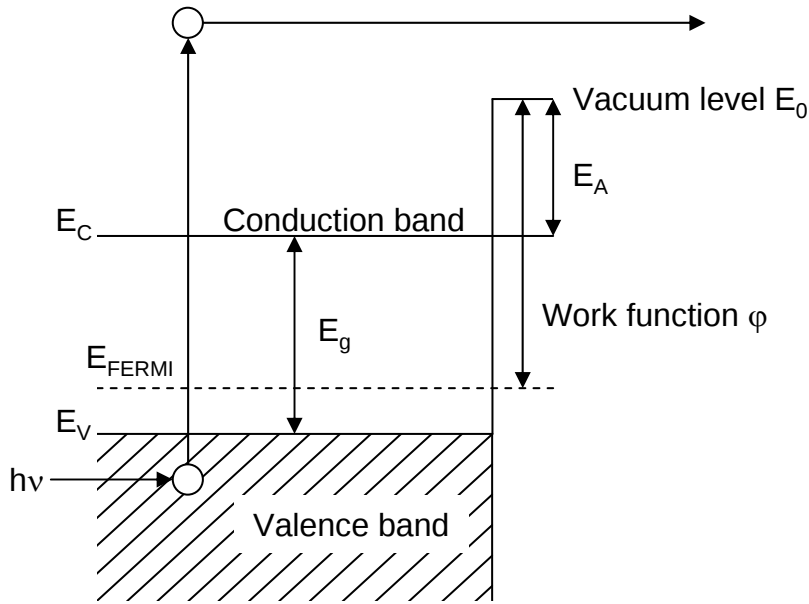


Figure 3.1: Electron emission from the valence band of an active material [61]. *See text.*

3.1.1 Photoelectric emission

The physical process at the base of a photomultiplier tube is electron emission (fig.3.1) from a material, defined as photocathode, excited by a photon beam. The photon energy $h\nu$, where ν is the frequency of the incident photon, following Einstein's law, must be equal to, or larger than, the work function ψ of the material, so that an electron can be emitted with energy:

$$E = h\nu - \psi. \quad (3.1)$$

The efficiency of this process is called quantum efficiency of the detector and represents the probability that an incoming photon will produce a free electron[61]:

$$\eta(\nu) = (1 - R) \frac{P_\nu}{k} \left(\frac{1}{1 + 1/kL} \right) P_s \quad (3.2)$$

where

R is the reflection coefficient of the entrance window,

k is the film absorption coefficient for photons,

P_ν is the probability of absorbed light quanta creating an electron with energy higher than vacuum level,

L is the mean escape length of excited electrons,

P_s is the probability that an excited electron, which reaches the photocathode surface, is emitted in vacuum.

Fig.3.2 shows a plot of quantum efficiency as a function of wavelength for a typical PMT.

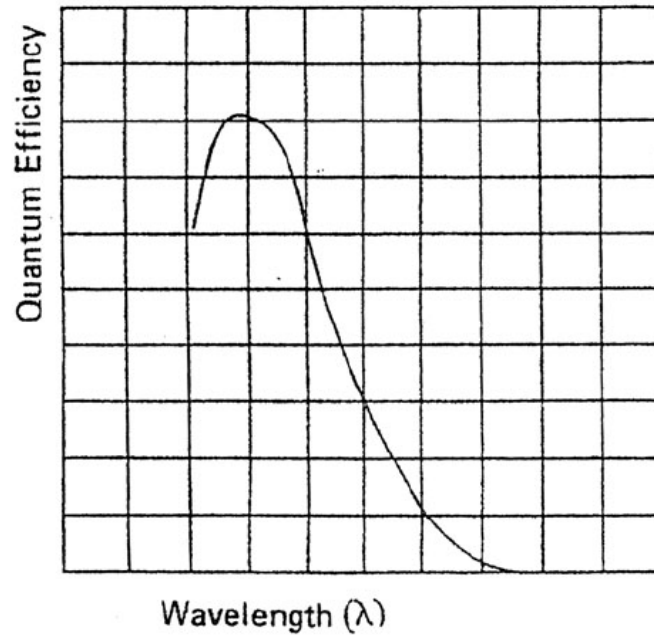


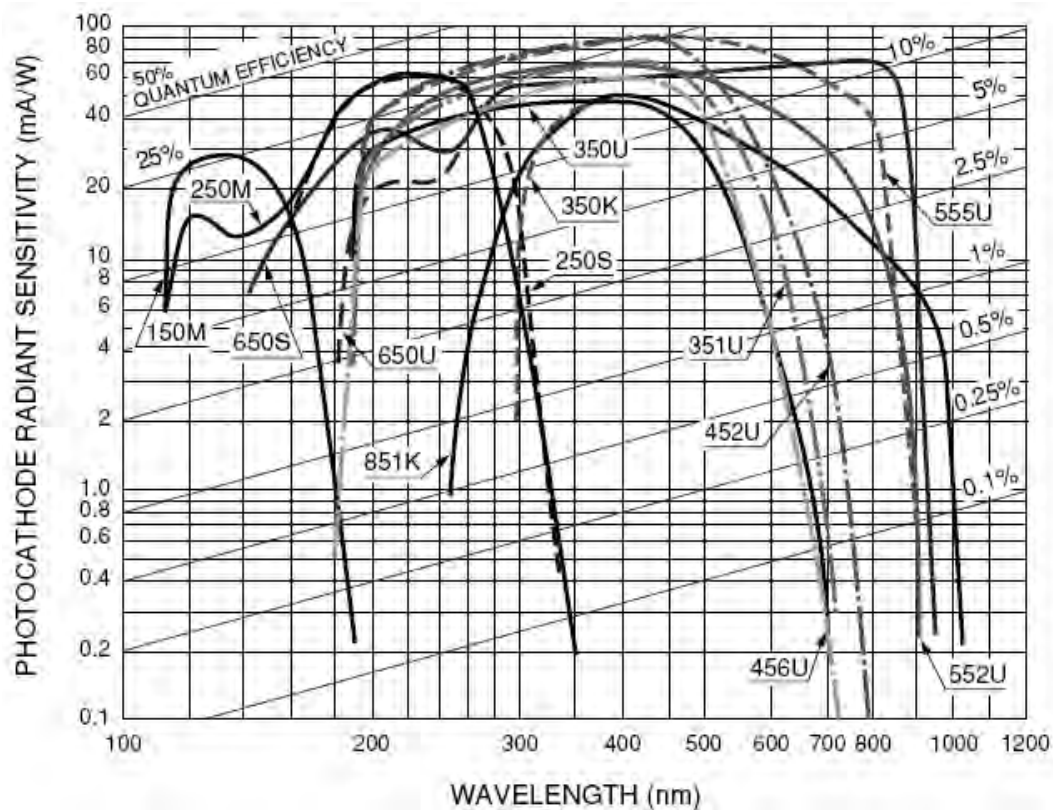
Figure 3.2: Photomultiplier quantum efficiency as a function of the incident photon wavelength. Figure taken from [62].

The critical variable is the length L of the electron path which depends on the thickness of the photocathode surface, the thinner the better. Usually cathodes of 20 nm thickness are used. The sensitivity range of the PMT depends on the photocathode coating material as shown in fig.3.3.

The produced electrons are then driven through the multiplier chain (fig.3.4) by a high electric field which focusses electrons directly on it. Each electrode of that chain, called dynode, has the same probability to produce electrons as the others. The emission curve of secondary electrons is shown in fig.3.5. It gives the average number of emitted electrons as a function of the applied voltage. The growth in the first part of the curve is related to the higher energy available to multiply electrons, while beyond a certain energy the number of a secondary electrons trapped inside the dynode starts to cause a decrease in the number of emitted electrons. The best dynode materials are Beryllium Oxide (BeO) or Magnesium Oxide (MgO) coated onto a nickel substrate. Since each dynode emits the same number of electrons δ , the amplification (gain) of the detector is written as δ^n , where n is the number of dynodes.

At the end of the chain the generated electrons are collected onto the anode. The photomultiplier output current is defined as:

$$I = G \cdot e \cdot N \quad (3.3)$$



Curve Code (S number)	Photocathode Material	Window Material
100M	Cs-I	MgF ₂
200S	Cs-Te	Quartz
200M	Cs-Te	MgF ₂
400K	Bialkali	Borosilicate
400U	Bialkali	UV
400S	Bialkali	Quartz
401K	High temp. bialkali	Borosilicate
500K (S-20)	Multialkali	Borosilicate
500U	Multialkali	UV
500S	Multialkali	Quartz
501K (S-25)	Multialkali	Borosilicate
502K	Multialkali	Borosilicate (prism)
700K (S-1)	Ag-O-Cs	Borosilicate
—	GaAsP(Cs)	—
—	GaAs(Cs)	—
—	InP/InGaAsP(Cs)	—
—	InP/InGaAs(Cs)	—

Figure 3.3: Typical PMT spectral response curves for different photocathode materials. Figure taken from [61].

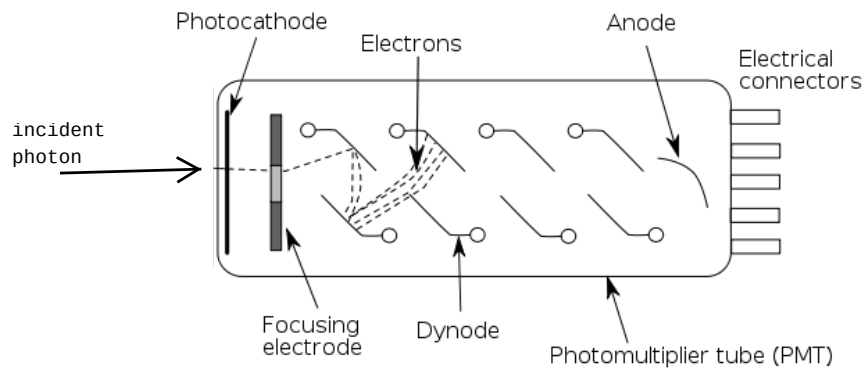


Figure 3.4: Dynode amplification chain for a linear photomultiplier tube. Figure taken from <http://it.wikipedia.org/wiki/File:Photomultipliertube.svg>.

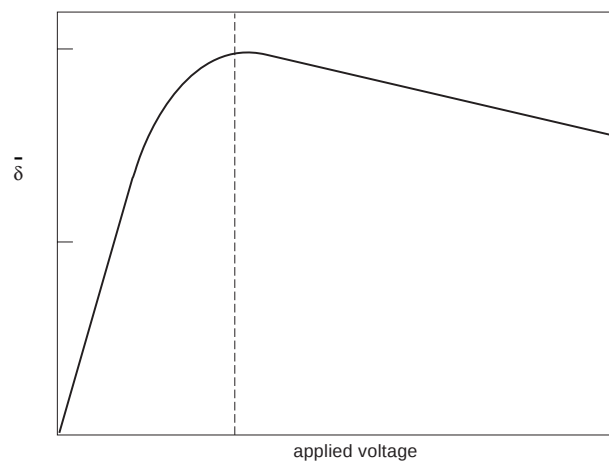


Figure 3.5: Secondary electron emission curve. Figure taken from [63]. See text.

where G is gain, e the electron charge, and N the number of incident photons per second. The electron emission follows a Poisson distribution as the number of incident photons.

3.1.2 Low background PMT

The photomultiplier used in the CAST experiment is a model 9893/350B Bialkali PMT made by Thorn-EMI (now ElectronTubes). It has a 52 mm diameter borosilicate entrance window with a blue-green sensitive photocathode having a maximum quantum efficiency of 25% at 350 nm (fig.3.6). The active diameter is subsequently electrostatically reduced to 9 mm. The main characteristics of this detector are reported in the following table 3.1:

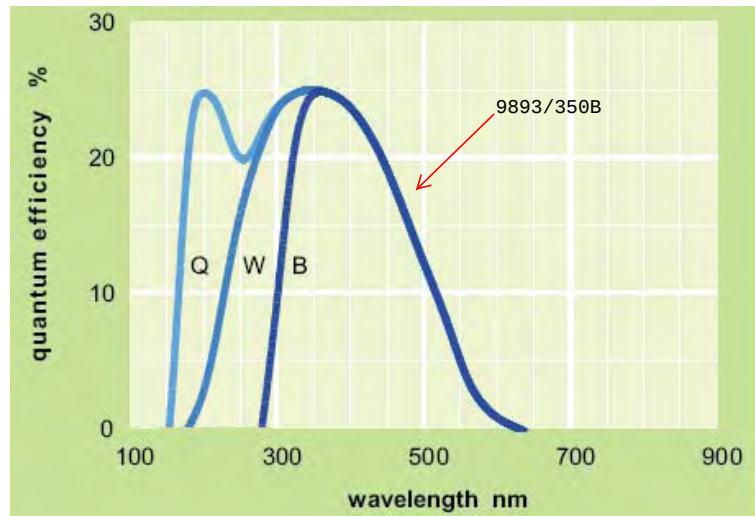


Figure 3.6: Quantum efficiency of the Thorn-Emi 9893/350B photomultiplier used in the CAST experiment. Figure taken from the PMT datasheet.

Gain	$2 \cdot 10^7$ @ -1950 V
Dark current	0.5 nA
Dark count rate @ 20°	40 Hz
Quantum efficiency @ 350 nm	25%
Working temperature	-30°C to 60°C
Maximum voltage	-3000 V

Table 3.1: Main characteristics of the Thorn-Emi Mod. 9893/350B photomultiplier tube.

The detector is operated at -22°C using a Peltier module mounted inside a cooled housing made also by Thorn-Emi (fig.3.7). This also provides shielding from external influences, such as ambient light, electric and magnetic fields.

Light shielding: The housing has, as its only entrance, an evacuated double-walled Pyrex window^(a) of 52 mm diameter in the front. On this window is attached a black painted aluminium flange with a small hole at its center (12 mm diameter) to connect a fiber collimator.

Electrostatic shielding: the housing is grounded and a gap of a few millimeters is present between the metal shielding and the PMT to reduce electronic noise.

Magnetic shielding: the housing is made of μ -metal to avoid the interference of external magnetic fields.

^(a)The window design prevents condensation on the cooled detector which would cause sparks among the dynodes and the anode.



Figure 3.7: The PMT housing. The evacuated double entrance window is visible at left. The HV voltage, output signal and Peltier supply connectors are on the rear panel.

3.1.3 Time response characteristics

Photomultiplier tubes have a very fast time response. The main contribution to the time response is the transit time required for a photoelectron to reach the anode passing through the dynode chain. This time depends on the dynode type and on the applied voltage. If the voltage increases, the electron speed increases thus shortening the time response. As reported in the characteristic table, the detector used has a transit time of 45 ns and a time resolution for a single electron of 3 ns.

3.1.4 Linearity

The PMT response exhibits a very good linearity since a fixed amount of electrons is produced for each incident photon. The sensor is thus capable to distinguish the number of photons incident on the active surface.

3.1.5 Stability

PMT performance deteriorates over time or as a consequence of UV illuminations. Deterioration depends on the repeated stress imposed by the supply voltage, by the currents and by the ambient temperature. Bialkali photomultiplier tubes are very sensitive

to UV light. In this region of the spectrum each incident photon could produce more than one electron. This will cause an increase of the detector noise since the cathode remains in an excited state even if it is in the dark. In this case, the return to normal background levels could take several hours.

3.1.6 Temperature

There are maximum and minimum temperatures above or below which the detector should not be used. Photomultiplier tubes must never be used above 70°C since at that temperature some elements of the photocathode will redistribute changing permanently the detector performance[64]. In addition at higher temperature the detector noise will increase. There is also a low temperature limitation. Although a lower detector temperature will decrease the noise level, there is a temperature below which the detector does not work any more. The low temperature limitation is imposed by the photocathode resistivity which increases when reducing the temperature. As resistivity increases, the voltage drop across the photocathode layers increases and the consequence is a distortion in the collecting field distribution. The minimum usable temperature, for the bialkali PMT, like the one used for CAST, is -50°C. Thus operating the PMT at a temperature lower than -30°C has no advantage since there is no a further reduction of background. When the detector is operated at low temperature a particular attention must be paid to avoid thermal shocks on the entrance glass window[65].

Another consequence of using the detector at low temperatures is the shift in its quantum efficiency. Usually the blue sensitivity is increased while the red one is decreased.

3.1.7 Magnetic Fields

An external magnetic field could distort the focussing electric field thus causing a reduction of the number of electrons reaching the first dynode. Obviously, the effect depends on the strength and orientation of the external magnetic field and on the type of PMT used. The shielding required can be determined by the relation:

$$\frac{H_{out}}{H_{int}} = \frac{\mu}{2} \frac{t}{d} \quad (3.4)$$

where H_{out} is the ambient field, H_{int} is the maximum allowed field, and μ , t , d are the shielding material permeability (10^4 typically), the thickness of the material and the diameter of the PMT shielding cylinder, respectively.

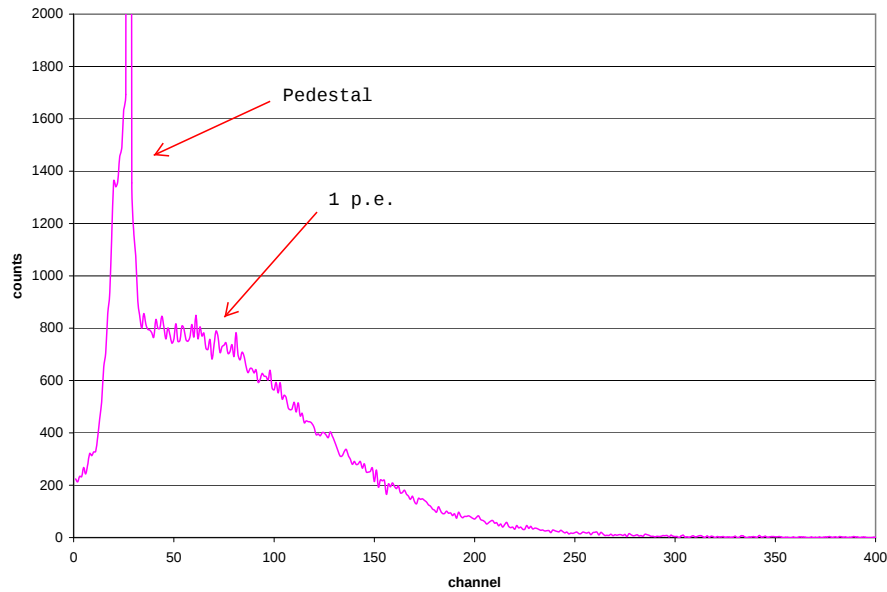


Figure 3.8: Pulse counting Poisson distribution of the PMT output signal. The data are taken using a blue LED ($\lambda=465$ nm) as a light source. The 1 photo-electron (p.e.) peak as well as the pedestal noise peak are shown. *See text.*

3.1.8 Single photon counting

The detector used in the CAST experiment is operated in single photon counting mode. In this mode the most important parameters are the quantum efficiency, the background noise level and the performance of the read-out electronic chain. As described in section 3.1.4 the response of the photocathode-dynodes chain is linear in the number of incident photons, thus the PMT detector can discriminate the number of photons arriving at the same time on it. Fig.3.8 shows an experimental distribution of the number of pulse counts at the end of the electronic read-out chain as a function of the pulse amplitude. The peak at the left is a pedestal due to electronic noise, while the curve at the right of the peak can be fitted with a Poisson distribution corresponding to an average number of 1 photo-electrons (p.e.). In order to reduce the electronic noise one can act on the signal threshold of the read-out circuitry.

3.1.9 Read-out electronic chain

The typical read-out circuit configuration used with the Thorn-Emi photomultiplier in single photon counting mode is shown in fig.3.9. In this chain the current pulses output from the PMT are converted into a voltage signal by a combination of a charge preampli-

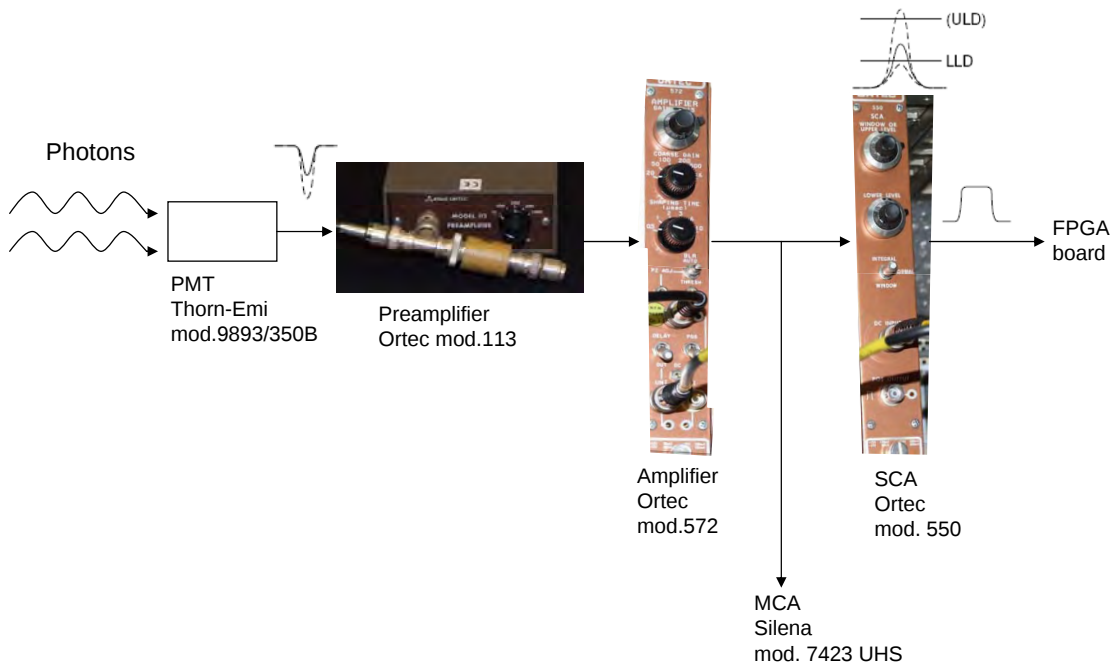


Figure 3.9: The basic read out chain for the photomultiplier tube. The main elements are a preamplifier-amplifier system, a discriminator or single channel analyzer (SCA) giving an output TTL signal. The resulting TTL pulse is counted by a NIM-standard counter or using a computer interface[61]. The amplifier output signal can also be acquired by a multichannel analyzer (MCA).

fier and of a fast amplifier module. This voltage signal is then formed by a pulse shaper giving a train of TTL pulses to be read by a Field Programmable Gate Array (FPGA) board or by a Nuclear Instrumentation Module (NIM) counter. An alternative to this scheme, used mainly for calibration, is to substitute the pulse shaper with a MultiChannel Analyzer (MCA). With the multichannel analyzer the distribution of the detector response to multiple incident photons is obtained.

Voltage bias

The PMT setup procedure consists in finding the voltage region in which the detector performs optimally. The choice of the biasing voltage value of the detector is a compromise between the quantum efficiency and the dark count rate, since both increase as the voltage increases. The high voltage module used is a NIM standard mod. N126 made by Caen with selectable polarity. To find the operating voltage the region between -1000 V and -2500 V was scanned, with the detector either in the dark or looking at a LED light source. The experimental setup is shown in fig.3.10. A multimode fiber is used to connect the detector to the light source. The light source was a 465 nm blue LED with 3 mW of

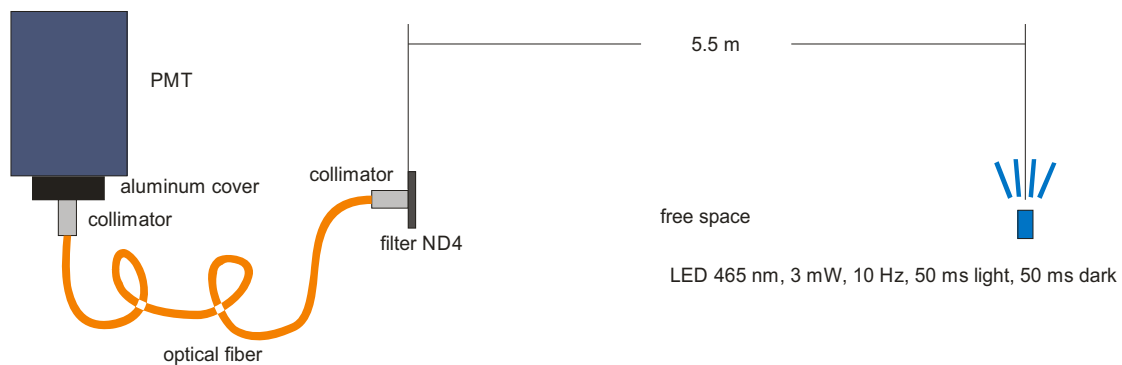


Figure 3.10: Scheme of the setup used for preliminary tests with the photomultiplier tube Thorn-Emi mod.9893/350B. ND4 = Neutral density filter with an attenuation factor of 10^4 . See text.

power. The results are reported in fig.3.11, where the working region is highlighted. The operating voltage of -1950 V was chosen.

Preamplifier and Amplifier

An important element to have a good photomultiplier tube output signal, is the right choice of the overall gain, sum of the electron multiplication gain and of the preamplifier plus amplifier gains. The signals obtained by this electronic chain are shown in fig.3.12, where the amplifier does not only increment the signal amplitude but also matches the impedance of the acquisition or pulse shaping system, filters the noise and limits the bandwidth. Fig.3.13 shows two actual oscilloscope traces giving the signal shape after the preamplifier (top green trace in the figure) and after the amplifier (bottom yellow trace). The charge preamplifier used is an Ortec mod.113 module with variable input capacity in order to better match the PMT output, converting the current output signal in voltage. To limit the loss of the signal information, minimizing the stray input capacitance, it is mounted as close as possible to the PMT anode. A low pass filter (1 M Ω , 1 nF) is used in series to filter the signal and reduce the high frequency noise.

The signal is then amplified using an inverting fast filter amplifier (mod. 572 made by Ortec) suitable for photon counting measurements thanks to its fast rise and decay times. The overall gain of the amplifier chain was 21. The choice of this amplification was imposed by the single photoelectron peak position in the multichannel analyzer. If the amplitude pulse is too high, the peak in the multichannel analyzer is shifted to higher channel values thus incrementing the electronic noise contribution. On the other hand, if the signal is too low it is spread among adjacent channels. The ideal choice is to have the signal pulse divided among a few channels.

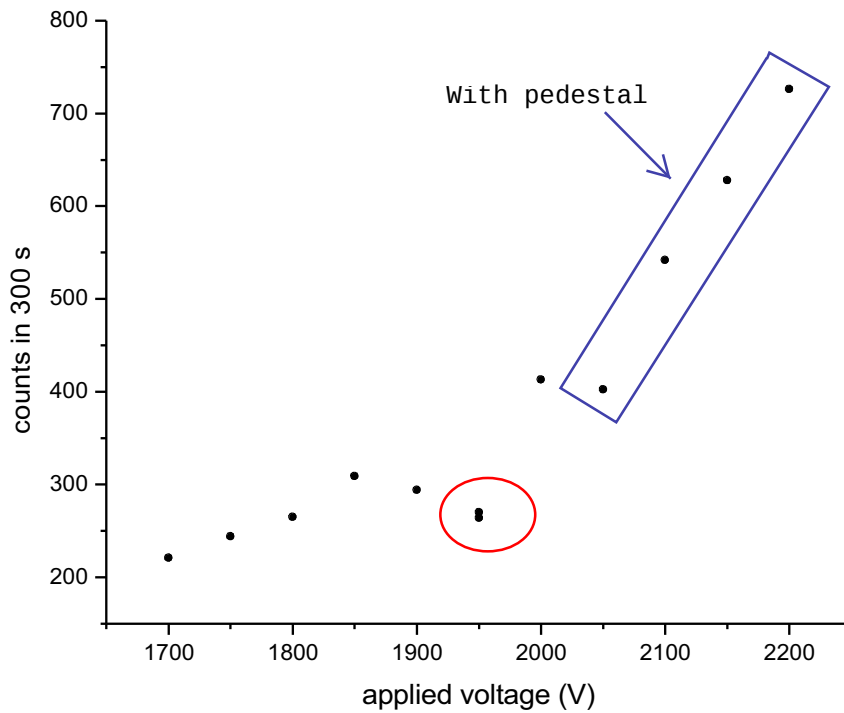


Figure 3.11: Dark count rate as a function of the applied high voltage. The data are taken with the detector at ambient temperature (22°C)

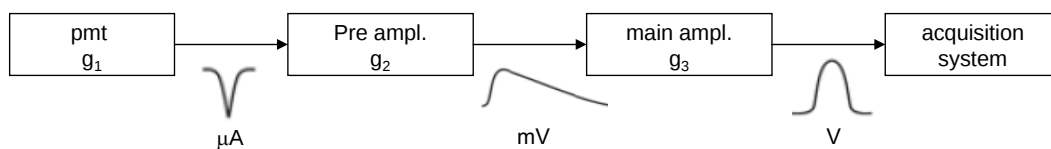


Figure 3.12: The preamplifier - amplifier chain. g_{1-3} are the gains of each module in the chain. Pulse shapes are reported along with the order of magnitude of their amplitude [66]. See text.

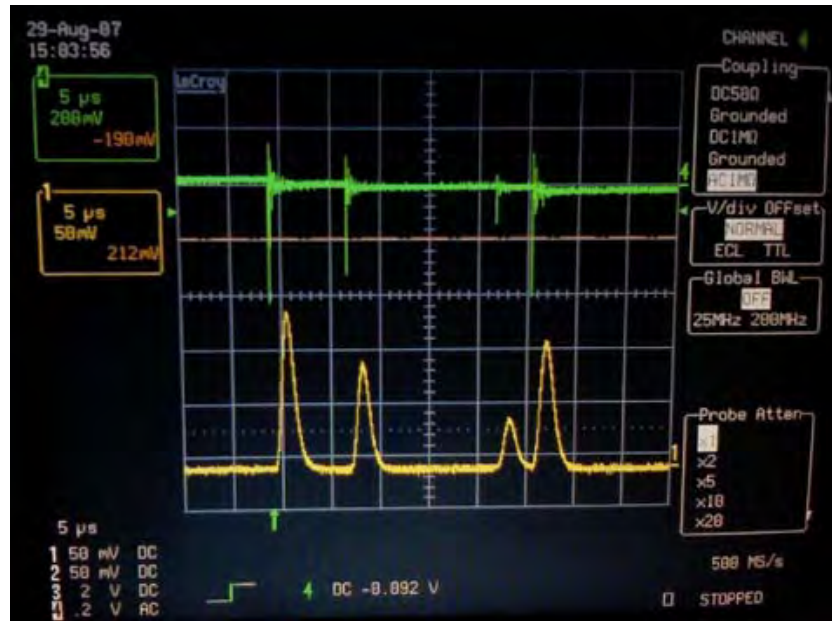


Figure 3.13: Oscilloscope traces of the PMT signals. The top (green) trace is the signal output from the preamplifier, while the bottom (yellow) trace is the signal after the amplifier module. *See text.*

MultiChannel Analyzer

Preliminary test measurements were done using a multi channel analyzer (mod. 7423 UHS by Silena). The MCA ADC^(b) output voltage range was 0-10 V and the number of channels was 1024. In this way two adjacent channels have a voltage difference of 0.9 mV. The test setup is the same as that of fig.3.10. Fig.3.14 shows the spectrum as seen by the MCA for a single photon peak. The solid black vertical line represents the threshold cut which is applied to the acquired data. The pedestal peak can be fitted with a double exponential decay (thick black curve), while the single photoelectron peak is fitted with a Poisson distribution:

$$y = \frac{A \cdot e^{-m} \cdot m^{\frac{x+B}{C}}}{\Gamma\left(\frac{x+B}{C} + 1\right)}, \quad (3.5)$$

where m is the mean number of counts per period, A is the normalization constant, equal to the number of counts, C is the bin size (in ADC channels) and B is the bin offset.

Another preliminary test was done illuminating the PMT using a blue LED switched at different frequencies, in order to verify the detector response sensitivity. The results are shown in fig.3.15. The lower curve is the number of counts measured with the blue LED switched at a frequency of 1 Hz, while the higher one is measured with 25 Hz switching frequency. The total peak counts show an increase of a factor 25 when the LED is switched

^(b) Analog to Digital Converter.

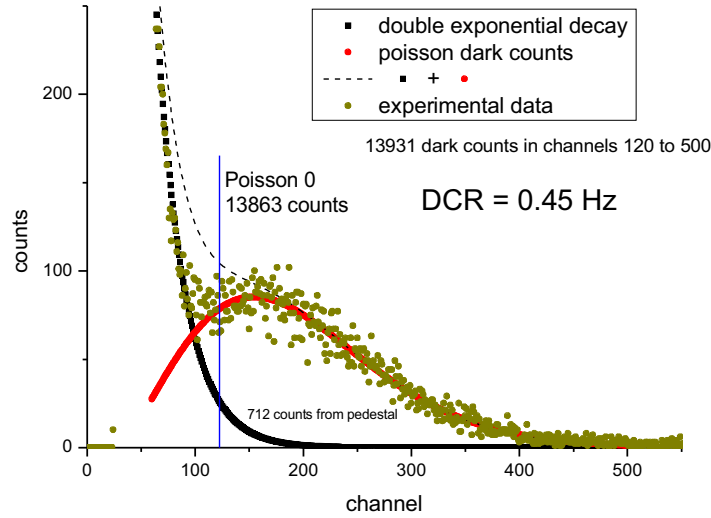


Figure 3.14: MCA spectrum for dark count measurements. The measured Dark Count Rate (DCR) is 0.45 Hz. *See text.*

at the higher frequency. It is possible to conclude that the sensors responds properly as the number of incident photons increases.

Single Channel Analyzer

The next step in the signal analysis is to form the gaussian signal output by the amplifier into TTL signals to be acquired by a computer based counting DAQ system. The TTL signal was obtained using a Single Channel Analyzer (SCA, mod. 550 made by Ortec). This module gives a standard TTL output pulse each time the input signals are above a selected lower threshold, and under a selected upper threshold (fig.3.16). The thresholds for the PMT used are chosen according to:

$$\begin{aligned}
 L &= ADC_{threshold}(ch) \times \Delta V_{ADC_{channel}}, \text{ giving} \\
 L_1 &= 140 \text{ mV} \\
 L_2 &= 400 \text{ mV}
 \end{aligned} \tag{3.6}$$

The amplitude of the photomultiplier tube signal is around 200 mV, thus with these thresholds the pedestal is cancelled out.

3.1.10 Data Analysis software

The output TTL pulses are acquired on a PC via a FPGA board (model 7831/R FPGA by National Instruments) and the data acquisition software was developed in Labview.

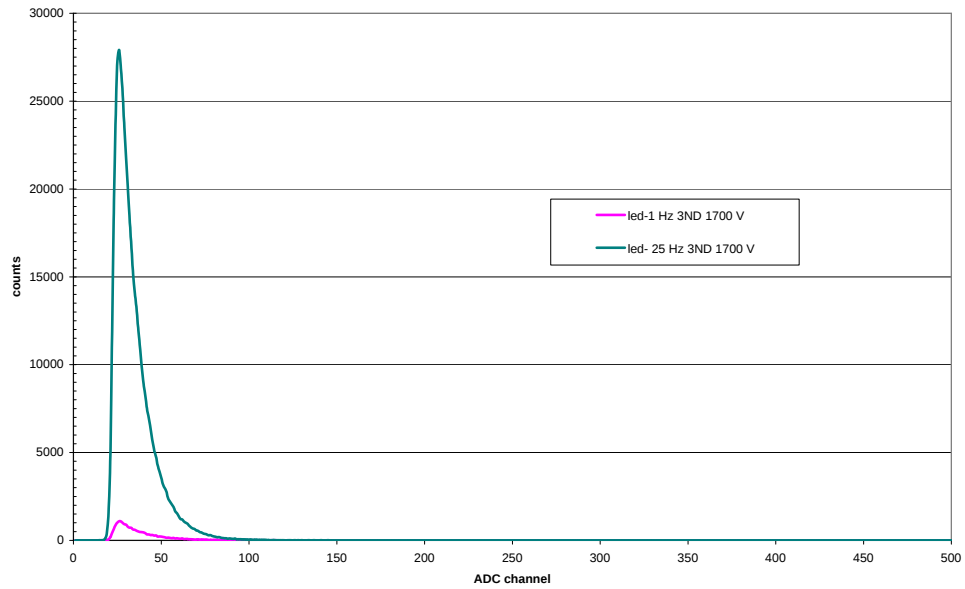


Figure 3.15: Spectrum obtained with a blue LED source switched at two different frequencies, 1 Hz and 25 Hz. A Neutral Density ND3 filter was placed in both cases in front of the PMT. The number of counted pulses increases by the same factor (25) as the LED frequency. The acquisition time was 300 s.

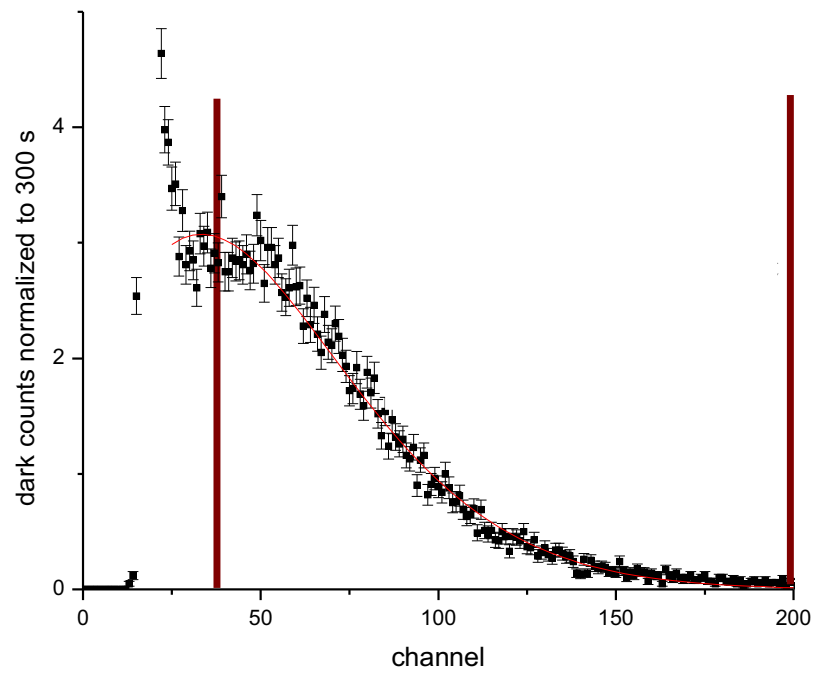


Figure 3.16: Lower and upper threshold cut. *See text.*

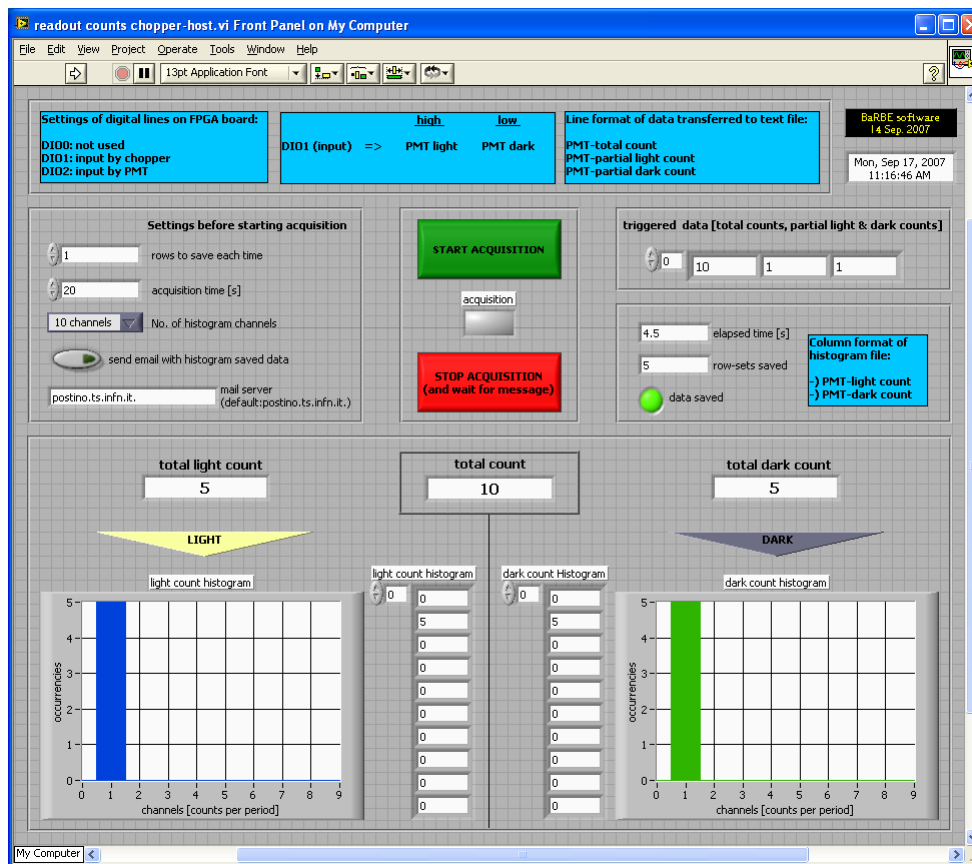


Figure 3.17: Screen shot of the acquisition software. The histogram plots are shown (bottom left and bottom right).

The preliminary test programs control the LED switching frequency and the acquisition time. During the first test a chopper was placed in front of the PMT. With this device the detector is for half the time in the dark and for the other half observing light. The goal is to have the detector active only during a short time window and to perform light and background counts simultaneously. The chopper frequency, and consequently the duration of the light window, was chosen in order to be half of the LED switching frequency. The acquisition software distributes the acquired data on an histogram plot, with the number of photons per pulse (1p.e., 2p.e., 3p.e., ...) on the x-axis and the number of occurrences on the y-axis (fig.3.17).

3.1.11 Afterpulses

Afterpulses are events delayed with respect to the incident photon beam output signal. In a PMT they are due to the electron excitation of the residual gas inside the vacuum tube. The main consequence is a false signal when the detector is used in single photon

mode, since this signal is not related to a real photon incident on the PMT photocathode. There are two types of afterpulses, the first happens a few nanoseconds after the signal pulse, the other after several microseconds. The first ones are due to elastic scattering of electrons on the first dynode, and this small delay is usually masked by the response circuitry. The second ones are due to residual gas ionization. These are positive ions which return to the photocathode thus producing electrons which are then amplified by the dynode chain.

Fig.3.18 shows a test measurement done with a blue LED flashing at 10 Hz. An excess of counts, with respect to the theoretical Poisson distribution, is seen in both the "light" and background curves in the field corresponding to two and three counts per period. These excess counts could be explained as afterpulsing events following one single count. An analysis done on the multiple pulses probability comparing it to the theoretical distribution, showed that the afterpulsing phenomenon is around 11% for single photon counts (see next chapter). The probability to have afterpulses at high rates is, in fact, very low and could be neglected with respect to the one affecting 1 p.e. or 2 p.e. peaks. The same measurement was repeated with a very small number of photons hitting the detector. An excess of counts, with the same probability, was seen also in this case. This last test was also very important in order to prove that the detector is able to discriminate very low-rate signals from background.

3.1.12 Dark counts

The dark current, current which flows through the detector when it is in complete darkness, is the main source of background in photomultiplier tubes. The main causes for the dark current are:

1. thermoionic emission current from photocathode and dynodes,
2. leakage current between the anode and the other electrodes inside the tube,
3. photocurrent from cathode scintillation,
4. field emission current,
5. ionization of residual gas inside the tube,
6. noise from trace radioactive elements possibly contained in the glass window.

The dark current varies with the applied voltage as shown in fig.3.19. The three regions refer to different applied voltages. At low voltage (region a) the main contribution is from leakage current, while in the middle region (b) the main contribution to the background is from thermoionic emission. This is the region which provides the best signal to noise

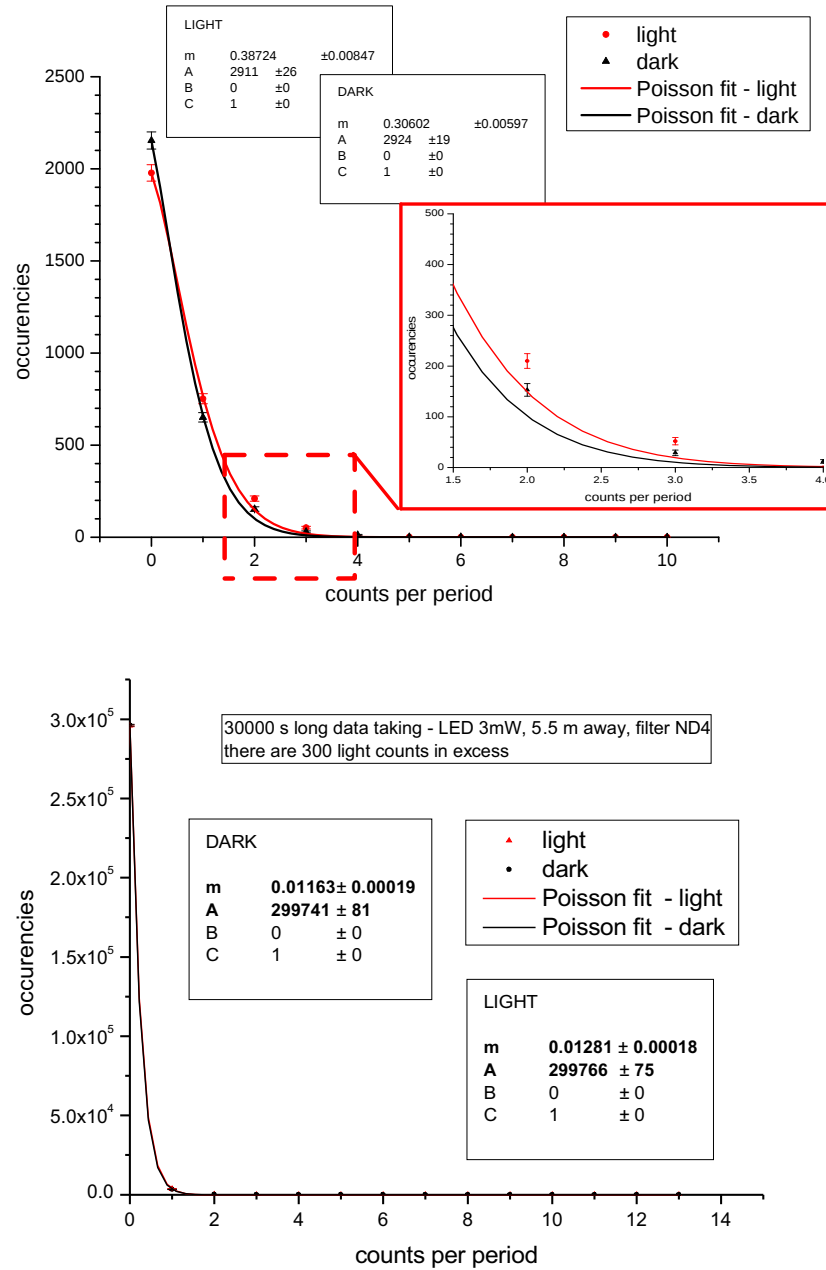


Figure 3.18: *Top:* Measurement of the afterpulsing effect using a 10 Hz flashing blue LED.
Bottom: Same measurement as in the previous plot but with a filter placed after the LED, in order to reduce the number of incoming photons. (See text).

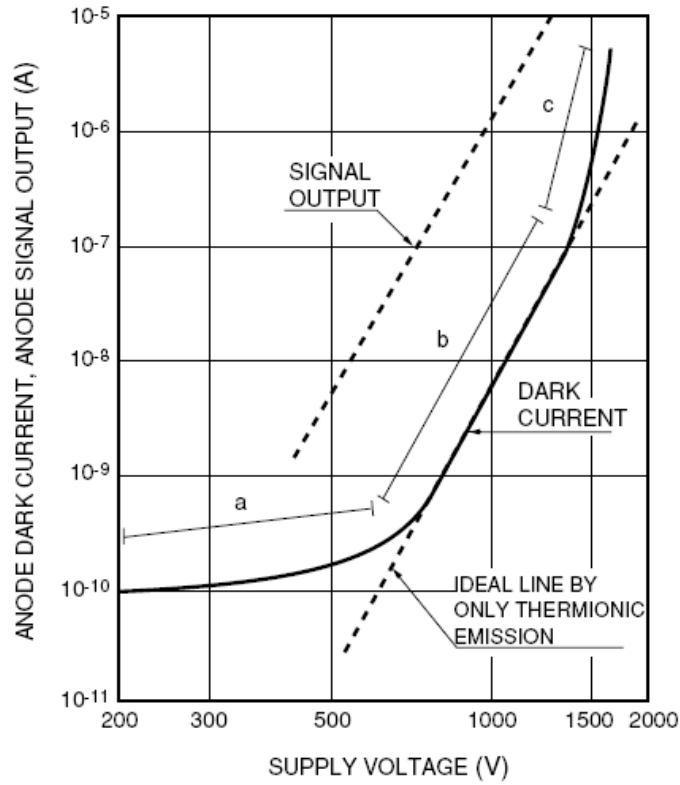


Figure 3.19: Dark current of a photomultiplier tube as a function of the applied voltage. Three main regions are visible: low voltage (a), operating voltage (b), high voltage (c). Figure taken from [61]. (See text).

ratio. The last region (c) is the high voltage one and the noise is due to the scintillation effects of the entrance window cathode.

Thermoionic emission: the work function (see eq.3.1) of the bialkali cathode material is very low and thus the thermal fluctuations can excite electrons which then escape from the cathode. The corresponding dark current is given by:

$$i_s = A \cdot T^{5/4} \cdot e^{-e\psi/kT}, \quad (3.7)$$

with e the electron charge and A a constant. When ψ is low, the photocathode response is extended to low energies but with an increase in dark current. On the other hand decreasing the temperature will lower the background (fig.3.20). This contribution to the detector background is independent of the detector gain or voltage since it is mainly due to photocathode emissions and not to dynodes emission, since dynodes have a smaller area.

Leakage current: the leakage current depends on the insulation material of the detector.

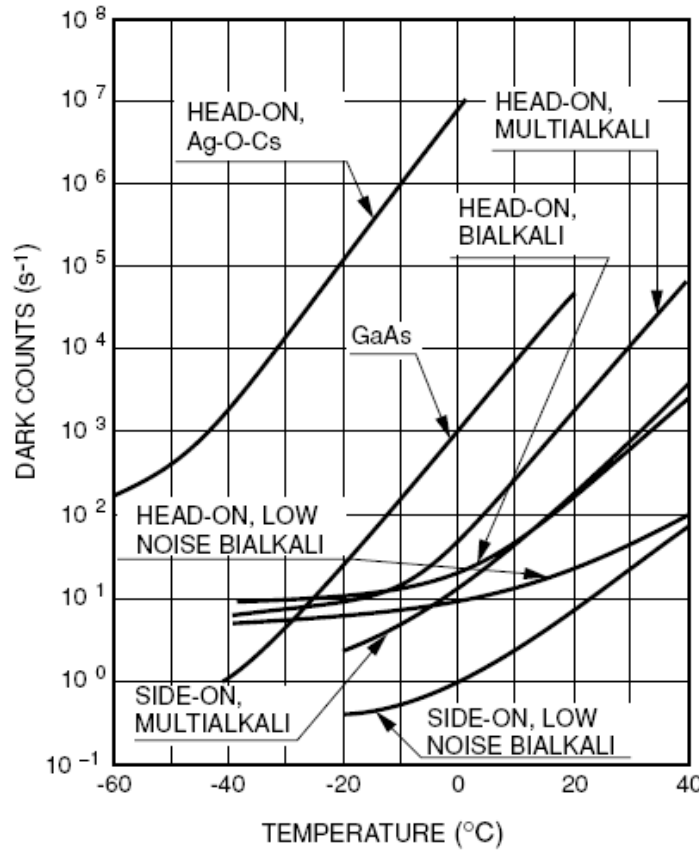


Figure 3.20: Temperature characteristics for dark current counts. Figure taken from [61]. (See text).

The better is the insulation the lower is the leakage current, following Ohm's law:

$$I_L = V/R \quad (3.8)$$

where R is the insulation resistance. Since $i_s \propto e^V$, i_L dominates only at low voltages.

Scintillation from the glass envelope: some electrons emitted from the dynodes or from the photocathode do not reach the anode but hit the glass envelope. If this happens then scintillation occurs. Usually the dark current is expressed in terms of the NEP (= Noise Equivalent Power), which is the value of incident light flux required to produce an output current equal to the noise current i_d :

$$NEP = \sqrt{2 \cdot e \cdot i_d \cdot \mu \cdot \Delta f} / S \quad (3.9)$$

where μ is the current amplification, Δf the bandwidth and S the anode sensitivity.

The dark count rate measured, for an acquisition time of 30000 seconds, with the PMT cooled at -20°C , is 0.35 ± 0.02 Hz. This is corrected for the afterpulsing effect. The error

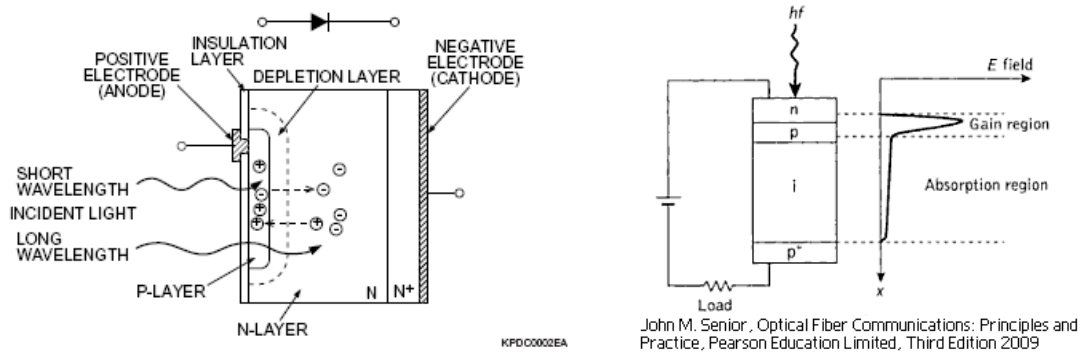


Figure 3.21: *Left:* Principle of operation of an avalanche photodetector. Figure taken from ref.[67].
Right: Electrical field distribution inside an APD.

is obtained considering a Poisson distribution of the events, and thus equal to $\sqrt{N}$ where N is the number of incidents photons.

3.2 Geiger mode Avalanche PhotoDiode (G-APD)

An avalanche diode is a semiconductor sensor used to count low rate signals (single photons) in the visible-near IR region. It can be considered the solid state evolution of the photomultiplier tube, moreover, it has several advantages, as it is very small, is radiation resistant and does not need a high voltage. This section describes the evolution of avalanche photodiodes, their main characteristics and the read-out electronics.

3.2.1 Principle of operation

The Avalanche PhotoDiode (APD) is a highly sensitive solid state device which converts the incoming light into an electric signal. From this point of view they can be considered as the semiconductor equivalent of the photomultiplier tube, moreover they have a high photon-electron conversion probability, which makes them capable of detecting low rate signals.

The principle of operation is shown in fig.3.21. The structure is a p-n junction which is depleted applying a reverse bias voltage^(c), the higher the voltage the larger the depleted region. In the resulting depleted region flows only a small reverse current due to thermally generated carries and to residual impurities. When a photon hits the surface of the p-n junction an electron-hole pair is created, which, due to the high electric field present

^(c)Under this voltage the holes are moved from the junction to the p side, while the electrons are driven to the n side.

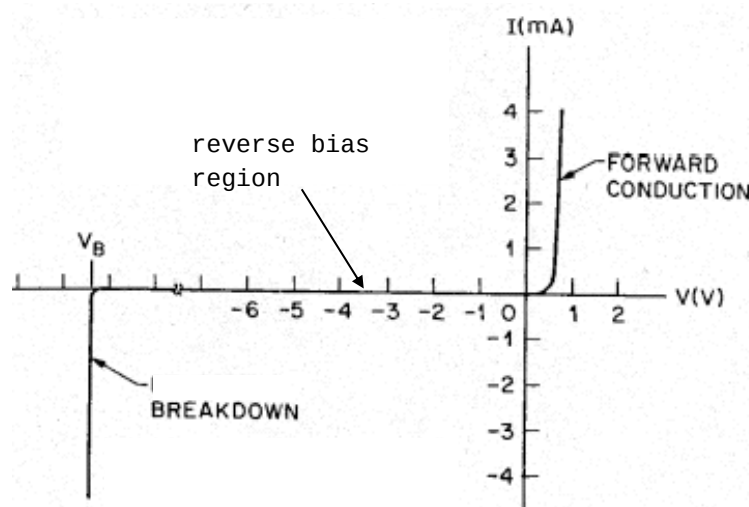


Figure 3.22: Diode current as a function of the applied voltage for an APD. The breakdown voltage is the one where an infinite gain is obtained. The reverse bias region is suitable to operate the detector as a photon counter with a gain around 100. Figure taken from http://www.ami.ac.uk/courses/topics/0181_ftes

in the depleted region, around 10^5 V/cm, is immediately accelerated. It acquires enough energy to ionize the lattice, starting an electron multiplication process. The produced electrons are subsequently collected at the anode where the signal is read. The main difference with respect to a photomultiplier tube is that a gain of the order of 10^3 is reached with an applied voltage of a few volts. To increase the gain up to $10^5 - 10^6$, the detector is operated in Geiger mode (see fig.3.22), which is obtained by setting the applied bias voltage larger than the breakdown voltage. The breakdown voltage is defined as the one where the gain becomes infinite. In this condition, after an ignition event in the depleted region, the current rises swiftly (in a few ns) to a macroscopic steady level in the milliamper range. The detector is no longer sensitive to other incoming photons, unless the avalanche is stopped. The stopping mechanism is called avalanche quenching (see section 3.2.2).

Despite the high sensitivity, these sensors when operated in Geiger mode are not able to distinguish the number of incoming photons, since the number of electron-hole pairs generated during an avalanche is independent on the number of generators.

3.2.2 Quenching circuit

There are two types of quenching circuits: active and passive. For both types the main functions must be:

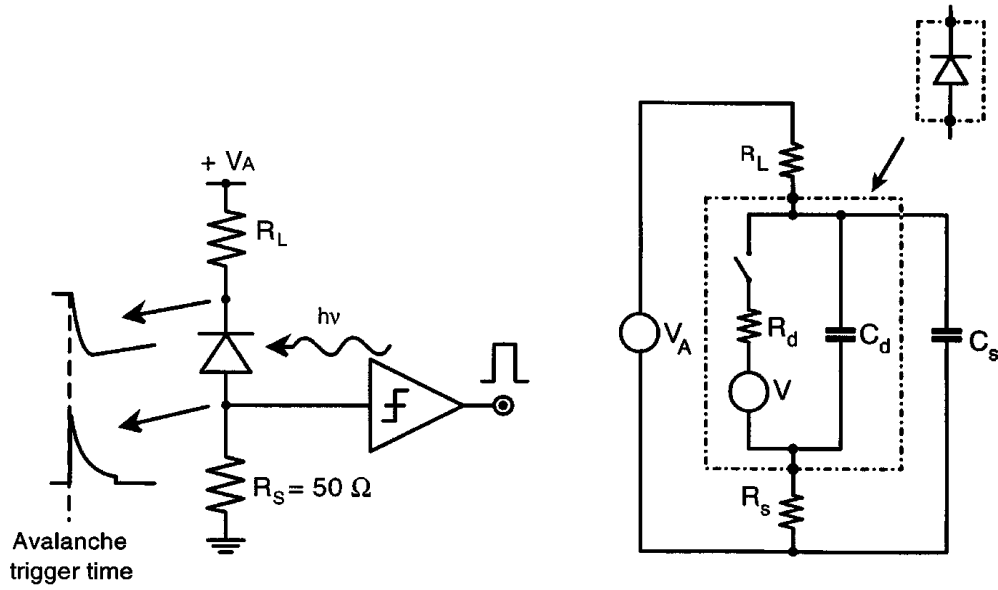


Figure 3.23: Passive quenching circuit scheme. *Left:* current mode output signal. *Right:* equivalent circuit for the passive quenched avalanche. R_d and C_d are the diode equivalent resistance and capacitance, while R_L is the load resistance and C_s is the stray capacitance (capacitance to ground of the diode terminal connected to R_L , typically a few picofarads). Figure taken from ref.[68].

- sensing the leading edge of the avalanche current,
- generating a standard output pulse well synchronized with the avalanche rise,
- quenching the avalanche by lowering the bias voltage, V_B , under the breakdown voltage, V_{bd} ,
- restoring the photodiode voltage to operational level.

Passive quenching circuit

This is the simplest quenching circuit and is composed of a single resistor in series with the G-APD. This quenching mechanism has been employed 40 years ago when these detectors were used for the first time. The avalanche current quenches itself simply by developing a voltage drop on a high impedance load as shown in fig.3.23 at left. At the right of fig.3.23 the sensor equivalent circuit is shown: the sensor is schematized with a resistor R_d , which value ranges from 500Ω to several hundred of $k\Omega$, and a capacitor C_d . It is reverse biased through a passive ballast resistor, R_L , having a resistance around $100 k\Omega$ or more. The avalanche is triggered when the switch of the detector equivalent circuit

is closed. The corresponding diode current, I_d , has the form (see fig.3.23 at left)[68]:

$$I_d(t) = \frac{V_d(t) - V_{bd}}{R_d} = \frac{V_{exc}(t)}{R_d}, \quad (3.10)$$

where V_d is the diode voltage, V_{bd} is the breakdown voltage and V_{exc} is the transient excess voltage. When the switch in the circuit is closed the capacitance discharges and V_d and I_d exponentially fall towards the asymptotic steady values V_f and I_f :

$$\begin{aligned} V_f &= V_{bd} + R_d I_f \\ I_f &= \frac{V_A - V_{bd}}{R_d + R_L} \simeq \frac{V_E}{R_L} \end{aligned} \quad (3.11)$$

since $R_L \gg R_d$, and V_A is the supply bias voltage and V_E is the excess bias voltage above breakdown[68]. When I_f is very small, then $V_f \approx V_{bd}$ and the number of carriers in the depleted region is again small. In particular, when $I_f < 100$ pA the probability that an electron or a hole creates an avalanche is almost zero, the avalanche is quenched. A very important parameter is then the value of R_L , the general rule is that $I_f < 20$ μ A and thus $R_L > 50$ k Ω / V_E .

The quenching time constant τ_q is defined by the total capacitance $C = C_T + C_s$ and the resistances R_d and R_L :

$$\tau_q = (C_T + C_s) \frac{R_d \cdot R_L}{R_d + R_L} \cong (C_T + C_s) R_d. \quad (3.12)$$

and usually is in the microsecond range. A photon which arrives during the recovery time is partly lost since it can create only a minor avalanche, so operates with a lower photon detector efficiency. This is an important consideration when the detector is used at high expected signal rates.

The output pulse from the passive quenching circuit is obtained inserting a low value resistor R_s in series with the ground load of the circuit. A good choice is 50 Ω since it matches also the cable impedance. This is called the voltage mode output, with a peak amplitude V_u :

$$V_u = (V_A - V_{bd} - I_f R_d) \frac{R_s}{R_L + R_s} \simeq V_E \frac{R_s}{R_L} \simeq I_f R_s. \quad (3.13)$$

Active quenching circuit

To avoid the drawback related to the slow recovery time after an avalanche, the active quenching circuit was designed. The idea is to sense the rise of an avalanche pulse and then to react back on the detector forcing the quenching and resetting it in a short time. The first active quenching circuit was developed in 1975 but it was for the first time applied to single photon detectors in 1981[69]. These circuits are based on fast semiconductor switches (double diffuse Metal Oxide Semiconductor Field Effect Transistor

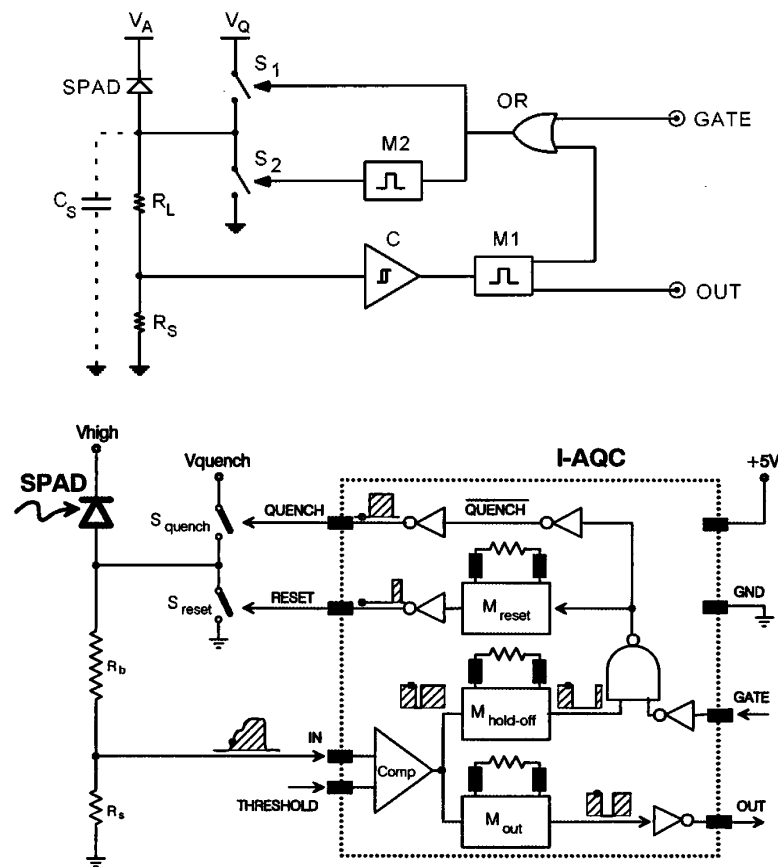


Figure 3.24: Active quenching circuit simplified scheme (top[69]) and more detailed scheme (bottom). Figure taken from ref.[70]. *See text.*

MOSFET). The scheme of an active quenching circuit is shown in fig.3.24. The rise of the avalanche pulse is sensed by a fast comparator whose output switches the bias voltage source to the breakdown voltage V_{bd} or below. After an hold-off time the voltage is switched back to the operational level. An output pulse is obtained from the comparator and is used for counting or timing purposes. The main advantages with respect to a passive quenching circuit are the fast response and the well known duration of the avalanche. In this way the detector is either fully dead or fully sensitive and there is no possibility of low efficiency counting, which could also be interpreted as correlated signal.

The active quenching circuit performs three functions: it amplifies tiny signals, it discriminates signals and it shapes the output pulses. This circuit is usually integrated on a chip bonded to the detector chip. In this way the problem of stray capacitance is solved. One of the innovations in the circuit is that it can operate at low voltage (5 V) with respect to the "high" voltage used to bias the detector.

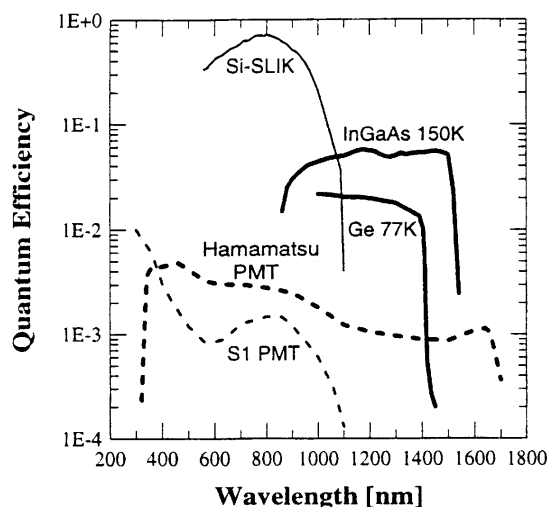


Figure 3.25: Wavelength response of avalanche photodiodes with different substrate materials. Figure taken from SPIE Proceedings Vol 2388 paper 09, 1995.

Summarizing, the basic actions of the active quenching circuit are:

1. the avalanche current lowers the voltage near the sensor;
2. the change in voltage switches the comparator output level to high (0 level = steady state);
3. the output of the comparator gives the input to quench the avalanche;
4. in this condition (switch closed) the detector is unsensitive to new incoming photons. The duration of the dead time is set to allow charges created during the avalanche to recombine (a few tenths of nanoseconds);
5. the detector is charged again through the resistance R_s , chosen very small so that the total recovery time is 2-3 ns[70, 71].

A combination of the two quenching circuits is presently also used. For instance a ballast resistor R_L is used to quench quickly the avalanche, while the active feedback circuit is used to restore the bias voltage lowering the time response.

3.2.3 Spectral sensitivity

The bulk of the sensor can be made of different materials. The choice depends on the desired range of wavelengths as shown in fig.3.25. Silicon photodetectors are more sensitive in the 300-900 nm range. In particular the thicker sensors (active diameter of 150-500

μm) are most sensitive in the infrared wavelength range, while the thinner ones (active diameter of 20-150 μm) have a fairly good efficiency in the visible and a lower efficiency, with respect to the thicker ones, at the 1064 nm wavelength. Germanium APDs (Ge-APD) have a high quantum efficiency at 1300 nm while InGaAs single photon detectors have 10% efficiency below 1500 nm.

3.2.4 Dark Count Rate

As photomultiplier tubes, the avalanche photodiode suffers also from the thermally generated currents even in absence of illumination. They represent the major source of background. The dark count rate depends on the temperature and on the applied bias voltage. It is divided in primary dark pulses and secondary dark pulses. Primary dark pulses are due to thermal fluctuations inside the semiconductor which are accelerated in the high electric field present in the depletion and start an avalanche. The number of thermally generated carriers per second is:

$$g(T) = \alpha_T \cdot n_i^2(T), \quad (3.14)$$

with α_T a constant and

$$n_i = 2 \left(\frac{2\pi kT}{\hbar^2} \right)^{3/2} (m_n m_p)^{3/4} e^{-E_g/2kT}, \quad (3.15)$$

where m_n is the neutron mass, m_p is the proton mass and E_g is the silicon energy gap (typically 1.14 eV). Decreasing the temperature of the detector will reduce this source of noise while increasing the excess voltage will raise it. This last effect is due to an enhancement of the thermally emitted carriers since the electric field is higher, and thus is larger the avalanche probability. The secondary dark pulses are due to the afterpulsing effect (see sec.3.2.5) and are the main source of noise at low temperature.

3.2.5 Trapping and afterpulsing effect

When an avalanche is triggered some of the generated carriers are trapped in the deep energy levels of the junction. This effect increases if there are impurities in the substrate or if the region is not fully evacuated of minority carriers. The trapped charges (fig.3.26) are then released, since they are in an excited state, with a statistically fluctuating delay, depending on the level involved. Released carriers are able to retrigger an avalanche, thus generating afterpulses related to a single event. The trapping probability is given by the product of the total charge flowing in the diode and the probability to have a single

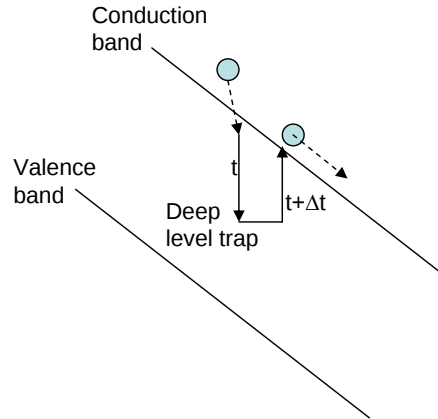


Figure 3.26: Scheme of the trapping mechanism in a silicon avalanche photodiode. The trapped carriers increase with the number of secondary carriers in the bulk[72].

trap P_{trap} :

$$P_{n_{trap}} = \frac{e^{-\lambda} \lambda^{n_{trap}}}{n_{trap}!}, \quad (3.16)$$

where $\lambda = n_{hole} \cdot P_{trap}$ and n_{hole} is the number of holes. Afterpulsing effects can be eliminated by choosing a passive quenching circuit, since the dead time is longer and the trapped carriers are no longer able to generate an avalanche. Moreover, afterpulsing effects increase with the number of carriers crossing the junction, or the total charge of the avalanche pulse. Therefore, if the time taken to quench the avalanche is too long, the number of trapped particles will increase considerably. The quenching time, in this perspective, must be as short as possible.

3.2.6 Thermal effects

An avalanche event could generate much power to be dissipated, especially if the detector is used in a high counting rate scenario and the thermalization is not fast enough. The thermal resistance from the diode junction to an external heat sink plays a key role. It strongly depends on the type of mounting (metal, ceramic, plastic) and is usually in the range 0.1–1°C /mW. The heating problem is enhanced if the detector is biased with a high voltage. The main consequence is a loss in linearity, however a permanent damage of the diode is also possible. To avoid these effects the quenching circuit must fulfill the following requirements:

1. the maximum amplitude of the quenching pulse must be 20-25 V,
2. the avalanche current must be quenched as soon as possible,



Figure 3.27: Views of the G-APD made by idQuantique. The active diameter of the sensor is $20\ \mu\text{m}$.

3. the hold-off time should be matched with the quenching time.

3.2.7 Linearity

The linearity of the response connecting the photon flux and the output count rate is limited by three factors: afterpulsing effects, dead time and detector heating. The afterpulsing effect can be cancelled by increasing the dead time or with a lower bias voltage, the dead time is fixed by the read-out circuit characteristics and is not a problem at low counting rates. For what concerns the detector heating, the total power dissipated in each avalanche pulse is given by:

$$P_{pulse} = V_E V_{bd} (C_s + C_d). \quad (3.17)$$

Therefore, to reduce the power dissipation, a lower voltage or lower capacity must be chosen, along with a good dissipative heat sink, like copper, which must be placed around the detector case. The thermal behaviour could also be significantly improved reducing the thermal capacity between the detector and the thermal cooler.

3.2.8 Test measurements on a G-APD sensor

The APD detector used along with the PMT, for preliminary tests and measurements at CAST, is a Geiger-mode avalanche photodiode module made by idQuantique, with an on-chip active quenching circuit and an integrated read-out electronic chain (model id100-20, see fig.3.27). The quantum efficiency of this sensor is shown in fig.3.28 and has a maximum at 530 nm of 35%. The sensor chip has an active area diameter of $20\ \mu\text{m}$. The detector quantum efficiency is the product of the probability that an incident photon creates a primary carrier pair, and the probability that this is able to start an avalanche. It

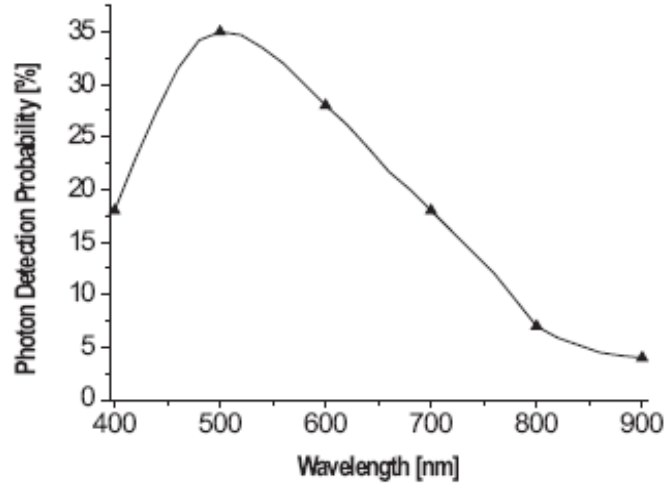


Figure 3.28: Quantum efficiency of the idQuantique sensor. Figure taken from [73].

is given by [69]:

$$P_b = 1 - e^{-(V_E/V_c)}, \quad (3.18)$$

which increases with an increase of the excess voltage. The characteristic voltage, V_c , depends on the depletion layer thicknesses and on the average ratio of the ionization coefficient of electrons to that of holes. Usually for a depletion region thickness of the order of 20-35 μm , V_c is in the range 6-16 V.

3.2.9 Read-out module

The id100-20 read-out circuit is integrated inside the module. It consists of three main elements, shown schematically in fig.3.29:

1. power stage,
2. control of the detector temperature,
3. read out and shaping of the output signal.

Power stage

The id100-20 module requires two power supply voltages: the bias voltage, -25.3 V, and the drive voltage, +5 V. To simplify the use of the detector, a single external power is used (+5V), subsequently converted via a DC/DC converter to the negative bias voltage, -25.3 V.

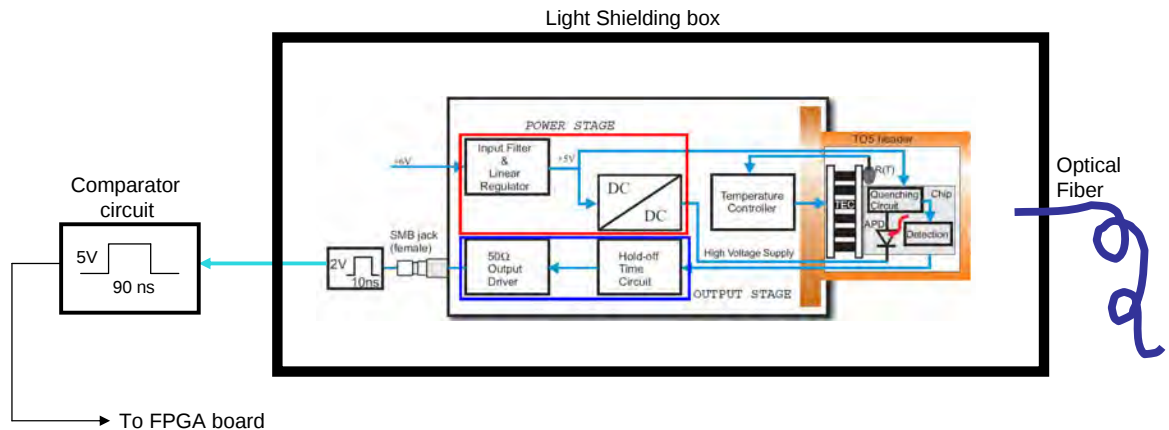


Figure 3.29: Scheme of the read-out circuitry of the id100-20 module. The id100-20 module (figure taken from [73], with its three main elements indicated) output signal is shaped in a TTL signal by a custom comparator circuit, in order to be read by a FPGA board. The sensor module is placed inside a black box in order to be shielded from ambient light, and is connected to the light source by an optical fiber. *See text.*

Temperature control

The detector is cooled down to 0°C using a Peltier effect Thermo Electric Cooler (TEC) on which the sensor is mounted. The temperature of the diode is continuously monitored using a thermistor ($R = 2.2 \text{ k}\Omega$ at room temperature) placed near the TEC. The temperature control is very important since the quantum efficiency depends on it. The value of the thermistor resistance is used to control the current flow in the Peltier module in order to keep the temperature fixed within 0.1°C .

Output stage

The sensor is equipped with an active quenching circuit bonded on the same chip, which also drives the output signal. The output signal has an amplitude of 2 V and a duration of 15 ns. The total detector dead time is 45 ns. The pulse is then converted in a standard TTL signal using a comparator circuit designed in our laboratory. The shaping circuit allows one to choose both the signal width and the signal threshold. Since the detector is operated in a low counting rate experiment a total duration of 90 ns was chosen. The measured output signal and the TTL-shaped one are shown in fig.3.30.

3.2.10 Measured Dark Count Rate

Fig.3.29 shows the experimental setup for the tests measurements with the id100-20. The detector is placed in a black box with a small entrance hole for the $200 \mu\text{m}$ fiber.

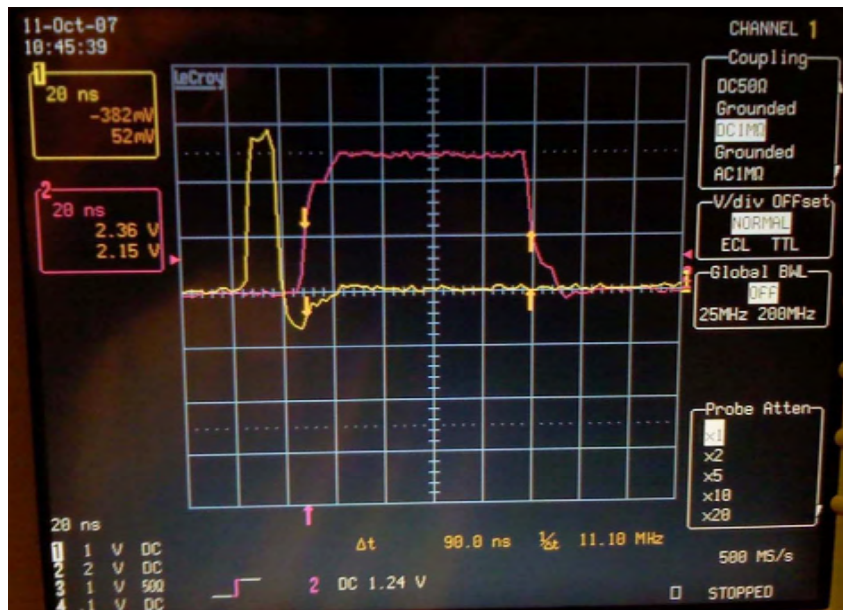


Figure 3.30: Photograph of the oscilloscope display. The yellow trace is the output signal from the front-end electronics of the id100-20. The 2 V, 15 ns width signal is then shaped by the custom made comparator circuit. The output signal is a 90 ns long TTL signal (red trace). *See text.*

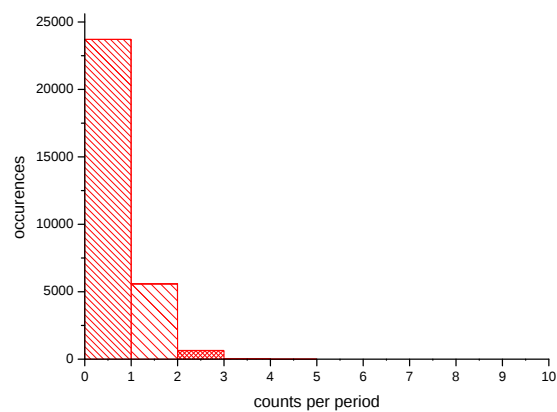


Figure 3.31: Dark count distribution per period (1s) for measurement lasting 30000 s.

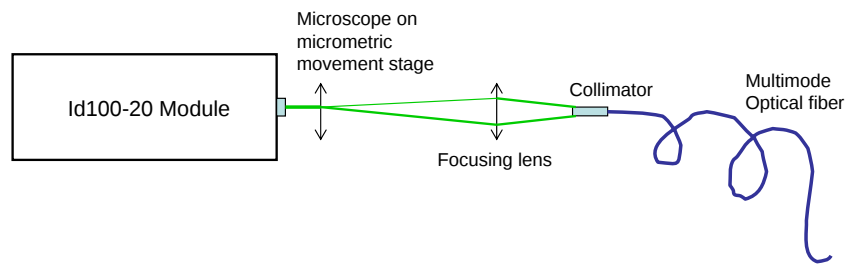


Figure 3.32: Focussing system for the id100-20. The signal is passed through an optical multimode fiber and then focussed using a lens into a microscope objective placed on a micrometric movement stage. The avalanche photodiode module is placed in the focal plane of the microscope.

The box is further covered with thick black cloths to improve the shielding from ambient light. The output TTL signals are acquired by a FPGA and a custom software. The dark count distribution, obtained in this condition and with the fiber closed, for the id100-20 APD sensor is shown in fig.3.31. Considering a Poisson distribution, the average background in 30000 s is 0.40 ± 0.02 Hz, not very different from the one measured for the photomultiplier.

3.2.11 Focussing system

The G-APD id100-20 sensor has a very small active area diameter, $20 \mu\text{m}$. A small area is advantageous since it reduces the dark count rate, however, it requires a focussing optics in order to be coupled to an optical fiber which has a core diameter of $200 \mu\text{m}$. The focussing system scheme is shown in fig.3.32. The fiber output is focussed using a fiber collimator into a microscope objective (20x magnification). The sensor active area is positioned in the focus of the objective using a micrometric movement stage. Several tests were carried out, changing the focal length of the microscope or adding more lenses to focus the fiber output beam prior to its injection in the objective. The geometrical efficiency of the detector is less than 0.01% and a sensor with a larger area is needed. In addition, part of the signal could be lost in the multimode fiber, in fact, even if the multimode fiber has a larger core size than a single mode fiber, which simplifies connections and also allows the use of lower-cost electronics, it supports more than one propagation mode thus it is limited by modal dispersion, having higher pulse spreading rates than single mode fiber. This will limit the information transmission capacity of multimode fibers.

Chapter 4

The BaRBE project and the measurements at CAST (2007-2008)

4.1 Experimental Setup

The BaRBE (Basso Rate Bassa Energia - Low Rate Low Energy) project is funded by INFN and its goal is to build a low background detection system for low-energy photons (a few eV at most), capable of single photon counting, with the aim of using it in those experimental situations where a very low rate of events is expected. The prototype system was constructed and characterized in Trieste, while the first measurements, in an actual experimental environment, were done after installing the apparatus on CAST at CERN. The main feature of the BaRBE setup is to share the same light source between two different detectors and to acquire simultaneously live ("light") and background data ("dark").

A scheme of the BaRBE apparatus, connected to a CAST magnet bore, is shown in fig.4.1 with an optical switch to share the input signal between the PMT and the G-APD detectors. This CAST magnet bore is coupled to a multimode optical fiber through a Galilean telescope. The other end of the fiber is connected to an optical switch with the output fibers matched to the photon sensors.

4.1.1 Galilean Telescope

A scheme and a picture of the Galilean telescope are shown in fig.4.2. It is used to couple the light coming out from the CAST magnet port (43 mm diameter) to a fiber collimator (9 mm diameter lens), connected to an optical fiber (200 μm core diameter). The coupling efficiency of the telescope was measured on a bench setup with a 1 mW green

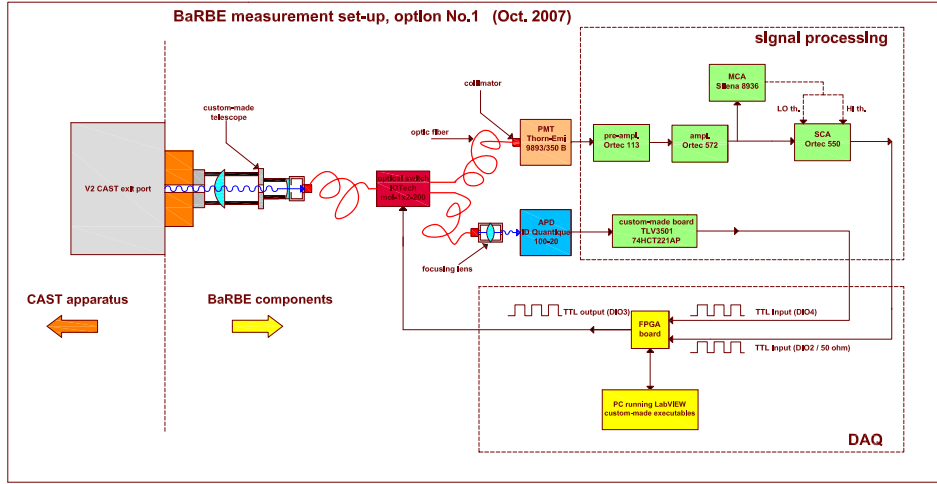


Figure 4.1: Schematic layout of the BaRBE setup as installed at CAST-CERN. A Galilean telescope couples optically the setup to the CAST magnet (to the left). An optical switch is used to share the input signal between the PMT and the G-APD and to acquire light and background data simultaneously. *See text.*

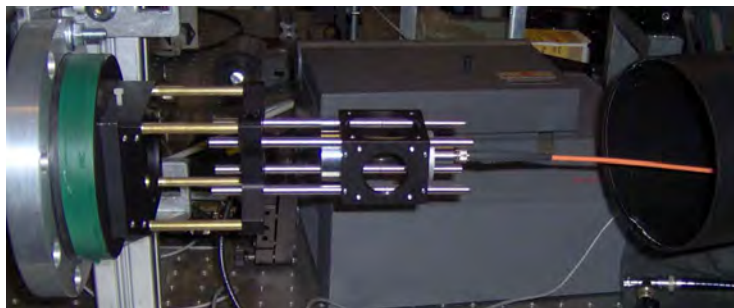
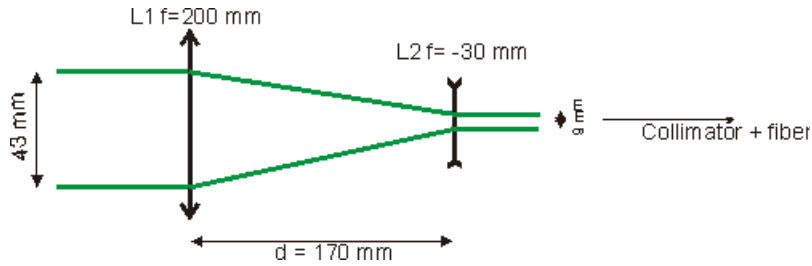


Figure 4.2: Galilean telescope installed on the CAST magnet bore to match the port diameter with the fiber one. In the upper picture the optical scheme of the telescope is shown.

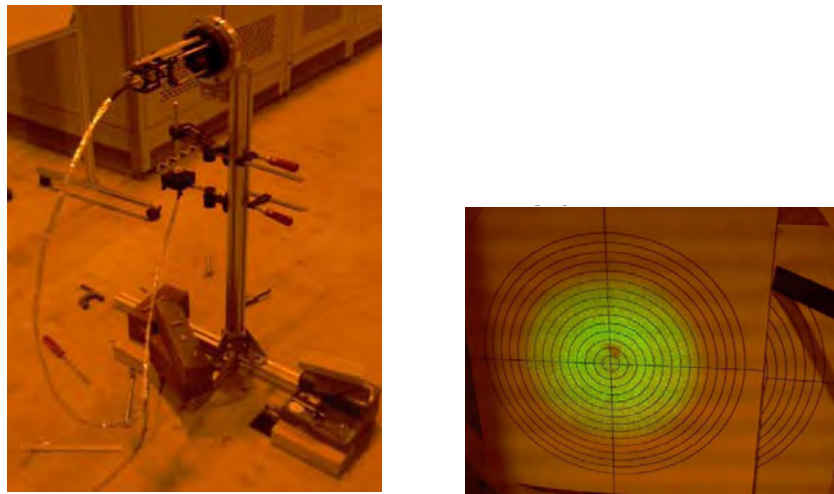


Figure 4.3: *Left:* picture of the telescope support for the alignment procedure carried out at CERN during November 2007. *Right:* green spot positioned on the 9 m away wall for alignment purposes. *See text.*

laser as a light source. The light power was measured before and after the telescope-fiber system, yielding a conservative estimate of 50% for the transmission efficiency.

Prior to attaching the telescope to the CAST magnet, an alignment procedure was carried out in order to ensure the parallelism between the optical axis of the telescope and the magnet axis. The procedure is divided in two steps.

1. Determining the "reference axis" of the telescope. With the help of surveyor the telescope was levelled and pointed at a wall distant 9 m (fig.4.3). A green laser beam was then shined at the wall through the telescope (fig.4.4). In this way the optical axis of the telescope was determined, as well as its misalignment with respect to an arbitrary reference axis determined by two points on the telescope structure.
2. Mounting the telescope on the magnet. Given the magnet axis direction the telescope optical axis was aligned with it by surveying the position of the reference axis determined in step 1.

The final misalignment between the telescope optical axis and the magnet axis was 5.6 mm to the left and 1.4 mm in the vertical direction (up) during the first measurement campaign (November 2007) and 1.2 mm to the left and 1.6 mm down during the second campaign (February-March 2008), when the procedure was repeated.

After the alignment, a blue LED was placed inside the telescope light-tight cover (fig.4.5) in order to check the integrity of the optical fiber attached to it, by switching it on when needed, and to verify the correct operation of the acquisition system. The 40 m long fiber was inserted in an aluminum flexible tube in order to prevent damages and to screen the

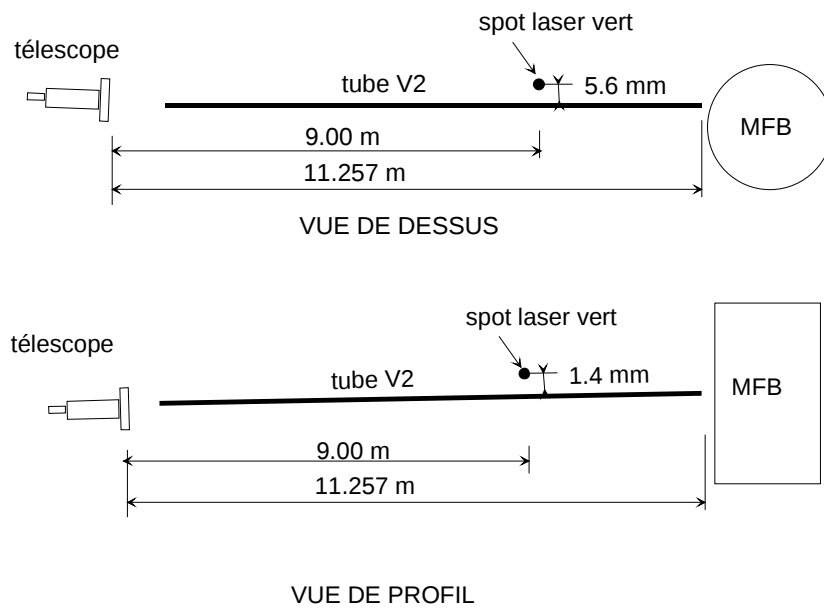


Figure 4.4: Surveyor's drawings of the Galilean telescope alignment on the CAST magnet. The horizontal and vertical misalignment with respect to the magnet axis, during the first measurement campaign, are shown. Figure taken from ref.[74]. See text.

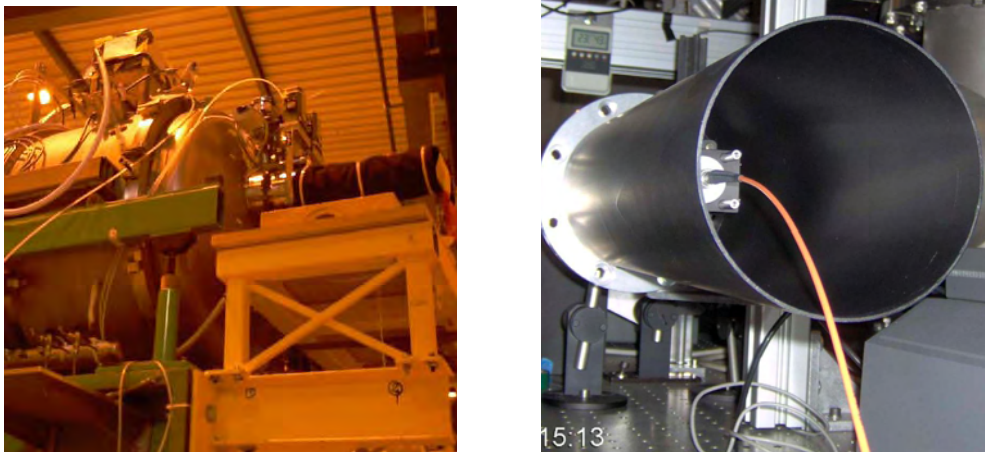


Figure 4.5: Left: telescope final cover. Right: fiber exiting the telescope. A blue LED was inserted in the cover to check the fiber integrity and the acquisition system.

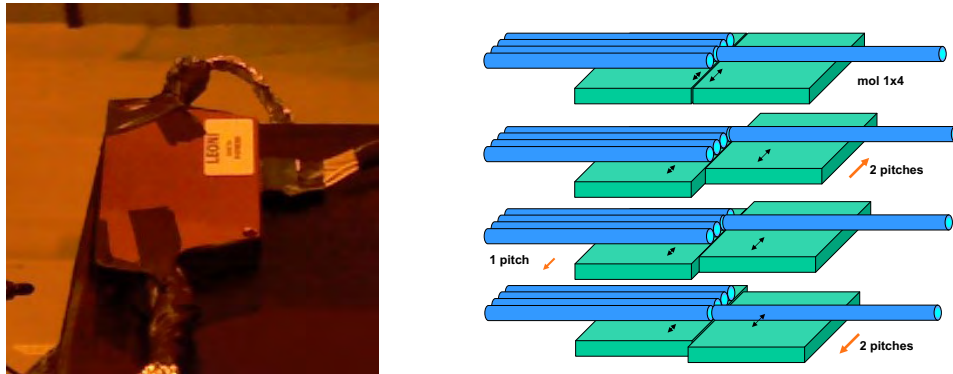


Figure 4.6: *Left:* optical switch used for the BaRBE system. *Right:* principle of operation of a piezo controlled optical switch. Figure taken from [75]. See text.

fiber from ambient light. An additional thick black cloth cover was added around the telescope to provide an additional shielding from the hall illumination (see fig.4.5).

4.1.2 Optical switch

The optical switch used is the 1x2mol model produced by Leoni GmbH, and is shown in fig.4.6 at left. It has one input multimode fiber and two multimode output fibers with a core diameter of $200\ \mu\text{m}$. The fiber properties are the same as the 40 meters long fiber. In this way the losses are minimized. The switch characteristics are summarized in the following table 4.1:

Maximum switching frequency	50 Hz
Transmission range	200 - 1600 nm
Insertion loss	0.9 dB
Switching time	10 ms
Channel cross-talk	< -45 dB

Table 4.1: Optical switch characteristics

The switch is controlled via a TTL signal given by a desktop computer through an FPGA board (National Instruments), which triggers the internal piezoelectric-actuated alignment of the fibers as shown in fig.4.6 at the right in the case of 4 output fibers. The principle is the same for two output fibers. In our set-up with the high level (+5V) the output fiber connected to the PMT is selected, while with the level low (0V) the G-APD fiber is chosen.

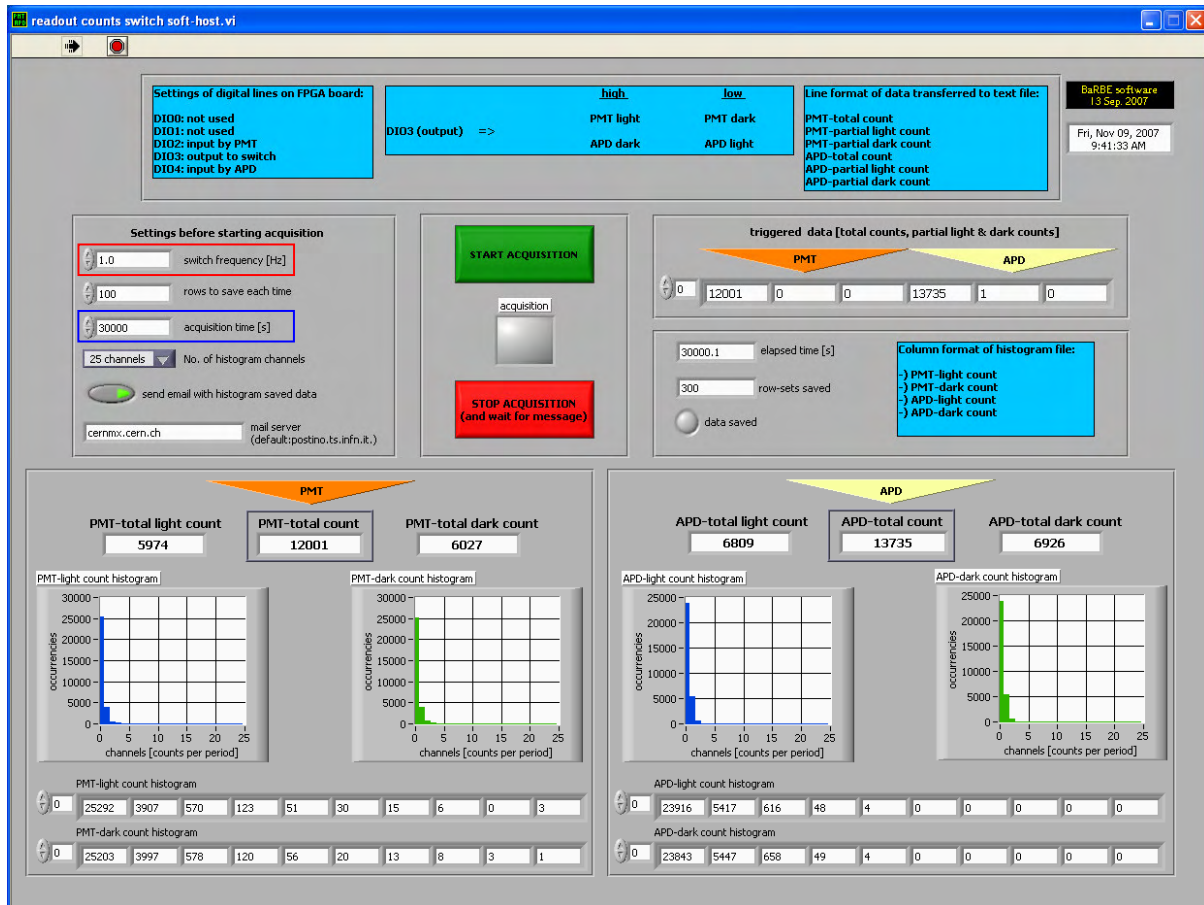


Figure 4.7: Screen shot of the acquisition software. The software controls the acquisition time (blue rectangle), the switching frequency (red rectangle) and acquires PMT and G-APD output signals separately. The acquired pulses are visualized in 4 histograms. *See text.*

4.1.3 Acquisition system

The TTL signals at the end of the PMT and G-APD read-out chains are acquired via a mod.7831/R FPGA board (made by National Instruments) and a Labview 8.2 software developed in our laboratory (see fig.4.7). This program has four main functions:

1. controlling the switching frequency. The 40 MHz FPGA clock allows a precise definition of the switching frequency,
2. setting the acquisition time,
3. acquiring the PMT/G-APD data separately. The duration of the output TTL signal is set in order to be correctly read by the FPGA,

4. carrying out a preliminary data analysis.

The raw data acquired are visualized in four separated histograms where the x-axis gives the number of counts per period (0, 1, 2 up to 10) and the y-axis gives the number of occurrences. The histograms are divided in *PMT light counts*, *PMT dark counts*, *APD light counts*, *APD dark counts*. The software gives also the total light and dark counts for each detector. These numbers are useful to immediately check for excess counts during the measurements, and to have an online display for the detector background.

4.2 Data taking at CAST

The BaRBE system was installed on the CAST magnet in November 2007 and also in February-March 2008. During the first campaign the system was mounted on the CAST V4 port on the sunrise side, opposite to the CCD detector, and the measurement lasted 8 days. The setup used is the one shown in fig.4.1. This allowed one to exploit the idea of using two detectors simultaneously, without losing in integration time, and also to acquire "light" and background data in the same experimental conditions.

The analysis of the preliminary data taken during November 2007 showed no signal above background, however, since the most part of the acquired data were background runs, a second series of measurements, in the same conditions in order to increase the statistics, was needed. The BaRBE low-energy setup was installed again on the CAST magnet during February-March 2008. The system was also placed on to the sunrise side but on the other port, facing the sunrise Micromegas (see chapter 2). Nine measurement days were completed.

The data taken during the both campaigns can be divided in background measurements during nighttime and daytime, "dummy" solar tracking, and "live" solar tracking.

Background measurements

A typical background measurement lasted 30000 s and was taken during nighttime and daytime.

In November 2007 a total of six sets of data were taken while changing the ambient conditions in order to study possible sources of noise:

- fiber not attached to the telescope but connected to the sensor system with the fiber closed and covered; in this way a possible source of background from the long fiber and the switching system was studied.
- Different lighting in the CAST hall: on, off and partially off^(a). This was done to test

^(a)Only half of the lights were switched on.

the influence on the sensor background of ambient lighting, and to search for the best conditions to be used during live solar tracking. It was also a test for sensor shielding.

- Magnet on but not moving in order to understand whether the magnetic field was a source of noise.

In February-March 2008 a total of 13 background measurements during nighttime and daytime were done, 8 with the magnetic field on and 5 with the field off. The measurements were performed with the magnet in the two "parking" positions: near the CAST control room (sunrise), and far from it (sunset).

Dummy solar tracking

The solar tracking is performed with the magnet not pointing to the Sun in order to understand whether the movement itself is a noise source. This background study was done both with the magnetic field on and off.

Live solar tracking

A total of 55000 seconds of solar tracking data were acquired with different ambient lighting conditions. The sensors acquired data only during sunset shifts, due to their position on the magnet sunrise side. During sunrise background or test measurement were carried out or the acquisition system was switched off. In February-March 2008 during two days of data taking the magnet pointed at the solar edge, 0.25° ^(b) to the left for the first 45 minutes of solar tracking and 0.25° ^(c) to the right for the remaining 45 minutes, instead of at the center of the Sun. The reason was the presence of a high solar activity in those days in these regions, which could have enhanced axion production.

4.3 Data analysis

The simplest way of analyzing the data is to consider the total light and dark counts and divide them by the corresponding acquisition time. The error bars are then calculated considering a Poisson distribution of the counts and are thus equal to $\sqrt{N}$, where N is the number of counts, also divided by the acquisition time. This is a raw way to look at the data since no correction is applied for the afterpulses generated by the sensor itself or by the electronic chain. One way to estimate the rate of the afterpulsing effect is to switch at high frequency, such as 100 Hz. In this condition the total acquisition time in

^(b)Considering the correction for atmospheric diffraction.

^(c)Considering the correction for atmospheric diffraction.

which the PMT is "active" is divided in 5 ms time windows. At a fixed count rate, such as the dark count rate, if events follow a Poisson distribution, two or more counts in each window are statistically suppressed. For instance, if the dark count rate is 0.4 Hz, the mean number of counts in 5 ms time window is $\lambda = 2 \cdot 10^{-3}$, and then the probability to see one count, following a Poisson distribution, is $P_1 = e^{-\lambda}\lambda = 2 \cdot 10^{-3}$, while the probability to see two counts is $P_2 = e^{-\lambda}\lambda^2/2! = 2 \cdot 10^{-6}$, and can be neglected. The residual multi-events peaks, with respect to the Poisson distribution, can be considered as due to afterpulsing. The number of afterpulses is defined for each channel, where a channel represents the number of counts per period (0 count, 1 count, 2counts,...), as:

$$N_{afterpulses} = \sum_{i=1}^{10} N_i(n_i - 1), \quad (4.1)$$

where N_i is the number of occurrences (each occurrence contains the number of pulses detected in a given time window) in the i th channel, and n_i is the number of the channel. In this way the sum of the number of occurrences in channels with more than one count are considered as real pulses followed by a number of afterpulses equal to $N_{afterpulses}$. It was seen that the afterpulsing effect accounts for about the 11% of the total counts measured. Keeping this in mind, the PMT number of counts was corrected for the afterpulsing effect, while the error bars are equal to the statistical error of the measured counts.

Another way to evaluate the mean number of light and dark counts, since the data follow a Poisson distribution, is to consider the following equation:

$$N_x = Ae^{-m}m^x/x! \quad (4.2)$$

where x is the channel number, N_x is the number of occurrences in that channel measured experimentally, A the normalization constant equal to the total number of windows opened during the acquisition time and decided before the measurement, and m is the mean number of counts in a period T , where T is equal to T_D/A , T_D being the light (dark) acquisition time. The afterpulsing problem is ruled out by solving eq.4.2 for the channel $x = 0$, since channel 0 is composed by the number of non-events, the number of periods in which there were no counts, and thus the measured occurrences do not have to be corrected for the afterpulsing effect.

The mean number of counts in a period obtained by solving eq.4.2 for $x=0$ is given by:

$$N_0 = Ae^{-m} \Rightarrow m = \ln(A) - \ln(N_0). \quad (4.3)$$

The rate of light and dark counts, m_n , is then obtained by dividing m by the factor $\frac{T_D}{A}$. When the switching frequency is 1 Hz, the total number of opened windows A corresponds also to the total acquisition time, which is twice of the total light (dark) acquisition time. In the following paragraphs the analysis just described is referred to as the " N_0

technique”.

The error on the number of counts depends on A , which is a function of the acquisition time and of the switching frequency, and on the number of counts in channel 0. Supposing that σ_A and σ_{T_D} are negligible with respect to the other error sources, and thus $\frac{T_D}{A}$ is fixed, the error on m_n is given by:

$$\begin{aligned} m_n &= \frac{A}{T_D} \ln \frac{N_0}{A(T_D, \nu)} \Rightarrow \\ dm_n &= \sqrt{\left(\frac{\partial m_n}{\partial N_0} \sigma_{N_0} \right)^2} \\ &= \frac{A}{T_D} \sqrt{\left(\frac{\sigma_{N_0}}{N_0} \right)^2} \\ &= \frac{1}{\sqrt{N_0}} \frac{A}{T_D}. \end{aligned} \quad (4.4)$$

The value of A which minimizes the error on the light (dark) count rate, is obtained recalling that $N_0 = Ae^{-m}$ and that $A = N_0 + \sum_i N_i$, which substituted in eq.4.4 gives:

$$\begin{aligned} dm_n &= \frac{1}{T_D} \frac{1}{\sqrt{Ae^{-m}}} [N_0 + \sum_i N_i] \\ &= \frac{1}{T_D} \frac{1}{\sqrt{Ae^{-m}}} (Ae^{-m} (1 + m + m^2/2! + \dots)) \\ &= \frac{1}{T_D} \sqrt{A} e^{m/2}, \end{aligned} \quad (4.5)$$

where $m = N_{ph}/A$ is the mean number of expected photons N_{ph} in a period:

$$dm_n = \frac{\sqrt{A}}{T_D} e^{-N_{ph}/2A}. \quad (4.6)$$

This expression has a minimum for $A = N_{ph}$, that is when the number of counting periods is equal to the number of photons N_{ph} counted during the acquisition time T_D . Fig.4.8 shows a plot of dm_n as a function of A . Doubling A will result in an increase of 10% in the error bar, while for $A=3N_{ph}$ the error bar becomes 24% higher. Since A also depends on the integration time, increasing T_D will reduce the error by the square root of T_D :

$$dm_n \propto \frac{1}{\sqrt{T_D}}, \quad (4.7)$$

thus if the acquisition time becomes 10 times larger the error is decreased only by a factor 3.

For what concerns the G-APD sensor, the afterpulsing effect is only a marginal problem. The main one is, in fact, the poor focussing onto the sensor active area, as pointed out in section 3.2.11. With this loss in efficiency the data acquired with this sensor are of

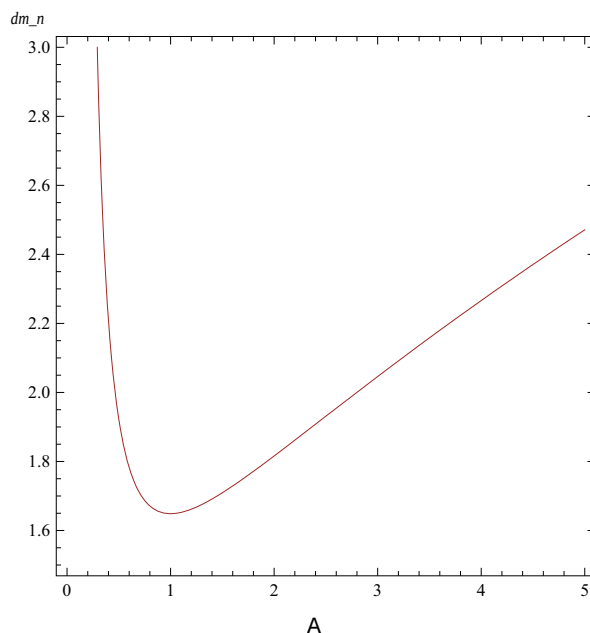


Figure 4.8: The error dm_n as a function of A . The expression of eq.4.6 is evaluated for $N_{ph} = 1$ and for $T_D = 1$ s. See text.

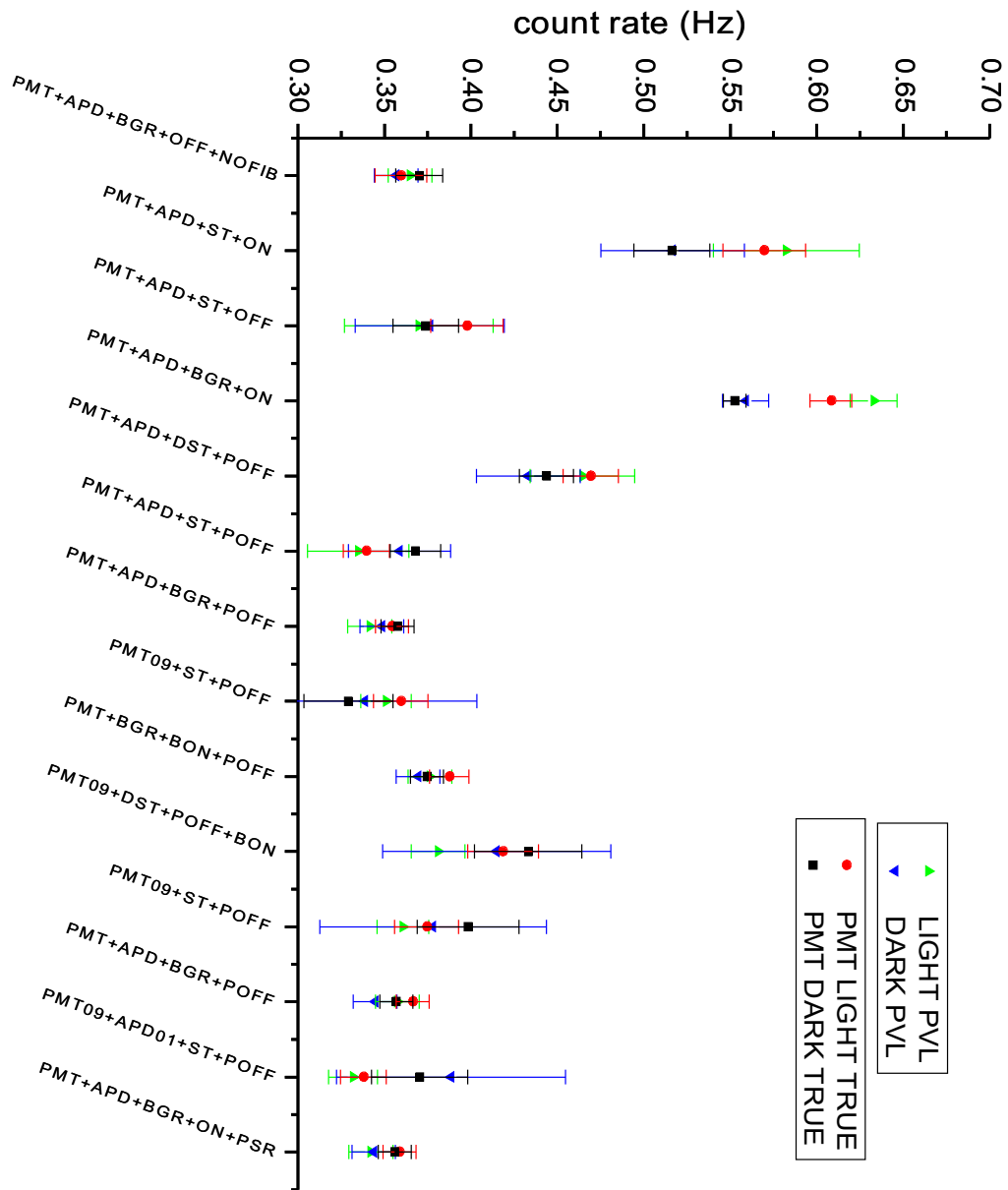
minor importance and only a raw data analysis is performed. Due to these reasons in the February-March 2008 campaign it was decided to use only the photomultiplier tube.

The temporal analysis of the data was also done to exclude an excess of counts for a small period and to check the behavior of the sensors during the acquisition time. For every window opened the difference between light and dark counts was calculated. The error was considered equal to the square root of the counts in the window, which is, for the most time, equal to the total number of counts (usually one per window). No excess of counts for a small period was found. In this analysis the occurrences were not corrected for the afterpulsing effect.

4.4 Results

During the first data taking at CAST, done in November 2007, there were mostly background acquisitions with different ambient conditions to understand possible noise sources. The results obtained with the PMT are shown in 4.9, where the two data analysis techniques are compared. The light (dark) count rates indicated with TRUE are referred to the raw analysis, without correction for the afterpulsing effect, while the light (dark)

Figure 4.9: Summary plot of the PMT results obtained with both analysis techniques described in the text during November 2007. The different types of measurements are reported on the x-axis. BGR = background run, ON = CAST hall lights on, OFF = CAST hall lights switched off, POFF = CAST hall lights partially switched off (half off and half on), ST = solar tracking, DST = dummy solar tracking, PMT09 = 90% of the acquisition time with the PMT looking at the magnet bore, APD01 = 10% of the acquisition time with the G-APD looking at the magnet bore, PSR = parking position.



count rates labelled PVL are the same data analyzed with the " N_0 technique", thus taking into account the afterpulsing effect and correcting for it. The background level evaluated in the raw way is higher because afterpulses are treated as true counts. In fig.4.9 the different types of measurements are indicated along the x-axis (see captions for the abbreviations), while the y-axis gives the light (dark) count rate.

The results obtained with the PMT are described below:

- **PMT + APD + BGR + OFF + NOFIB:** both the PMT and the APD are used with the switch at a frequency of 1 Hz. The measurement was 30000 s long and was taken during the night and with the light in the hall completely off. The fiber was not attached to the telescope and the dark counts are due to the thermal electrons released in the gas. No difference is seen between light and dark counts as expected. The background obtained is the same as that measured in the laboratory in Trieste.
- **PMT + APD + ST + ON & PMT + APD + ST + OFF:** the second and third measurements corresponds to the same solar tracking run, divided in two parts in order to study the effect of ambient lighting during the movement of the magnet. In the first part the lights in the experimental hall were switched on, while they were off in the second part. It is clear that the light shielding of the detector was not enough since there is a visible increase in both dark and light counts with the illumination on.
- **PMT + APD + BGR + ON:** this long background measurement, taken during the night with hall lights on, confirmed that the detector shielding was insufficient.
- **PMT + APD + DST + POFF:** this dummy solar tracking measurement performed with hall lights partially off showed that the source of noise was light leaking at the detector and not the movement of the magnet. A better shielding with thick black cloth was therefore put around the detector.
- **PMT + APD + ST + POFF:** this solar tracking run showed that the shielding was effective for the detector and the same background was measured as that obtained in the Trieste laboratory.
- **PMT + APD + BGR + POFF:** this measurement done during nighttime, in the same conditions of the previous solar tracking, confirmed the shielding performance.
- **PMT09 + ST + POFF:** since the G-APD focussing problem was not solved it was decided to remove the detector in order to attempt to improve the focussing system, while the PMT kept acquiring data. To increase the statistics, the time acquisition of "light" counts was increased by 90% thus maintaining a small percentage of dark counts acquisition. This is the reason for the large error bars of dark counts with respect to light one. The switching frequency was 0.2 Hz.

- **PMT + BGR + BON + POFF**: to study the influence of the magnetic field on the sensor noise a background measurement was done with magnetic field on. There was a slightly increase in dark and light counts, which remained however statistically compatible with the previous measurements.
- **PMT09 + DST + POFF + BON**: another dummy solar tracking was done with the magnetic field on and the light partially off. There is no difference between this measurement and the following one, which is a real solar tracking.
- **PMT + APD + BGR + POFF & PMT09 + APD01 + ST + POFF**: the last two measurements were done with the PMT and the G-APD together but with a switching frequency of 0.2 Hz and 90% of the light time focussed on the PMT during the solar tracking.
- **PMT + APD + BGR + ON + PSR**: this is the last measurement done during the night with all the lights in the hall switched on and the magnet in the parking position. The background level is the same as the first run.

The difference between light and dark counts is shown in fig.4.10 for the measurements with the PMT. The error bars reported are 1σ significance. No signal was seen above background for all the measurement runs. It was not possible to add together all the solar tracking runs since the data were taken in different conditions. The global Dark Count Rate (DCR) obtained is given below as the weighted average of the DCRs obtained in each single background run:

$$\text{DCR} = 0.39 \pm 0.04 \text{ Hz} \quad (4.8)$$

Similarly the average Light Count Rate (LCR) relative to "live" solar tracking runs is:

$$\text{LCR} = 0.36 \pm 0.07 \text{ Hz}. \quad (4.9)$$

There is no statistically significant difference between LCR and DCR (1σ errors are given). The same type of measurements just described were also done with the G-APD sensor. Results are shown in fig.4.11 and fig.4.12. The same DCR as in the PMT case is obtained. The active area of the G-APD was $314 \mu\text{m}^2$ and sufficient focussing could not be reached to match the light collection efficiency obtained with the PMT. It seems at this moment, that the only way to solve the focus problem on the G-APD is to go to a large active area detector, since $20 \mu\text{m}$ are too small to attach a fiber directly on the sensor surface. It was therefore decided not to use the G-APD in the subsequent measurement runs.

The results for the February-March campaign are shown in fig.4.13. Different types of measurements are done with lights on and off, and with the presence of the magnetic

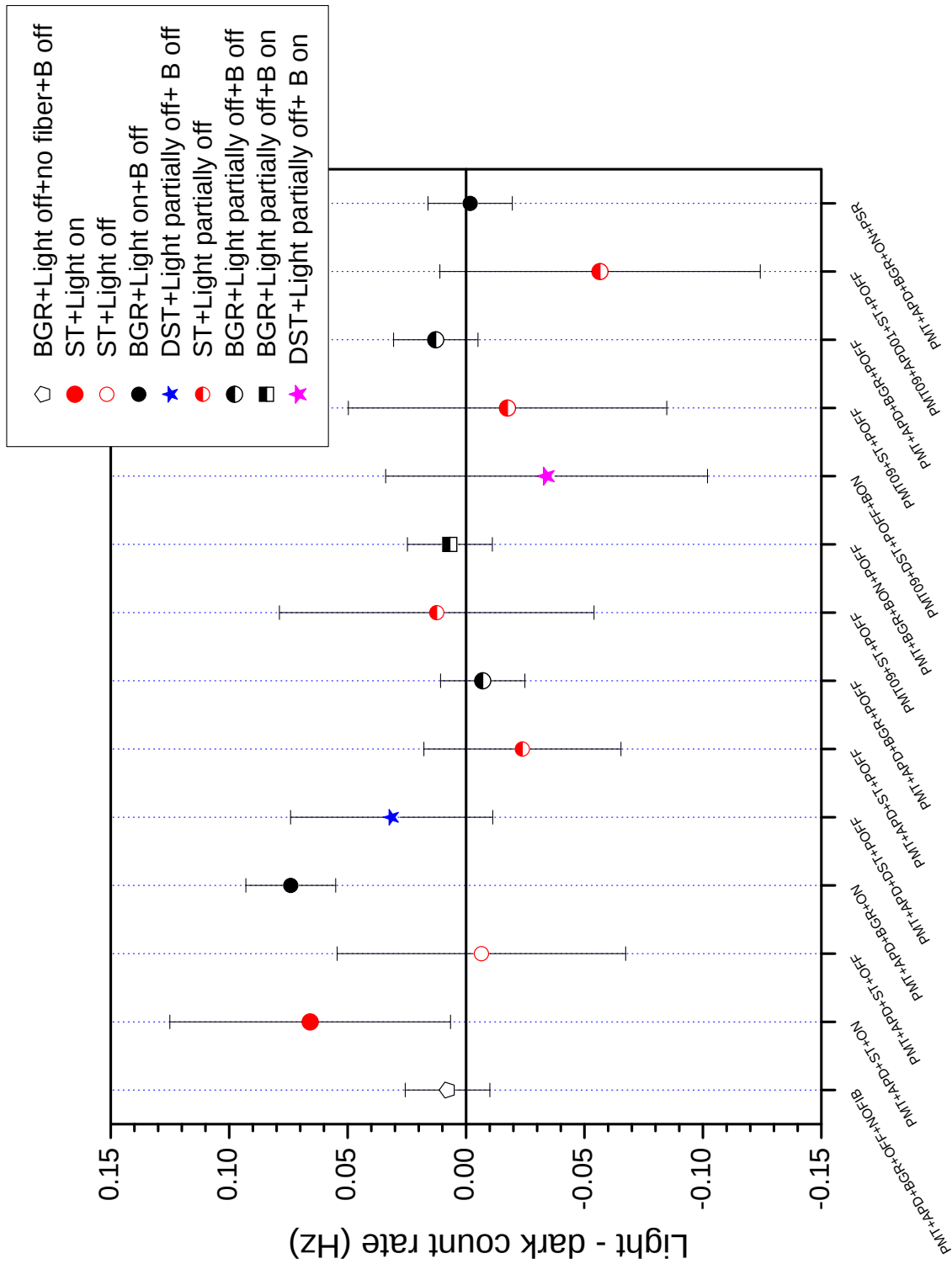


Figure 4.10: Difference between light and dark counts for all the different types of measurements done in November 2007. Similar measurements are plotted with the same symbol (see legend). The error bars correspond to 1σ error. No statistically significant excess of counts is observed.

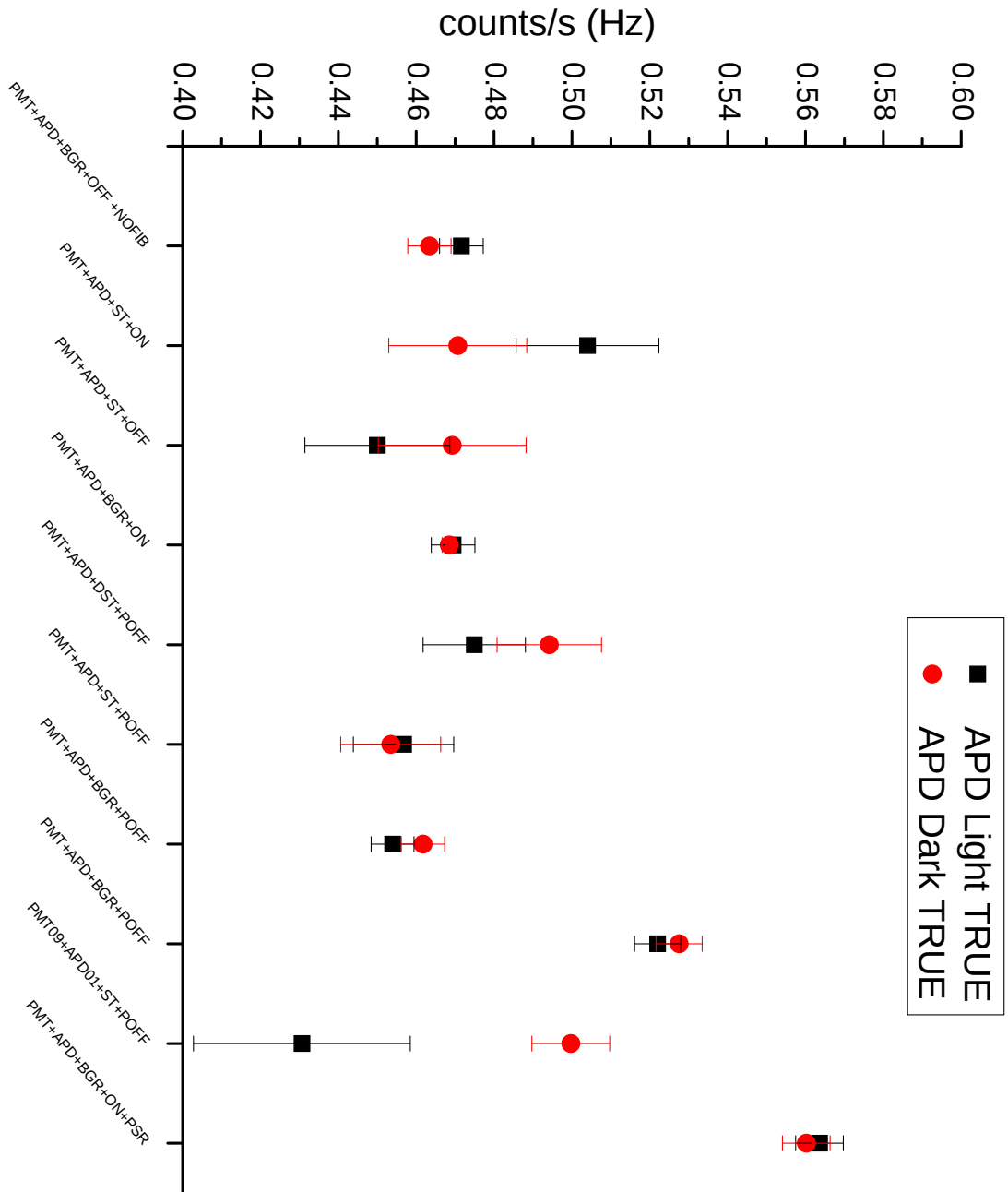


Figure 4.11: Raw estimates of the light and dark count rates obtained with the G-APD sensor. No correction for the afterpulsing effect was applied since there is a significant loss in efficiency due to poor focussing. Error bars correspond to 1σ errors.

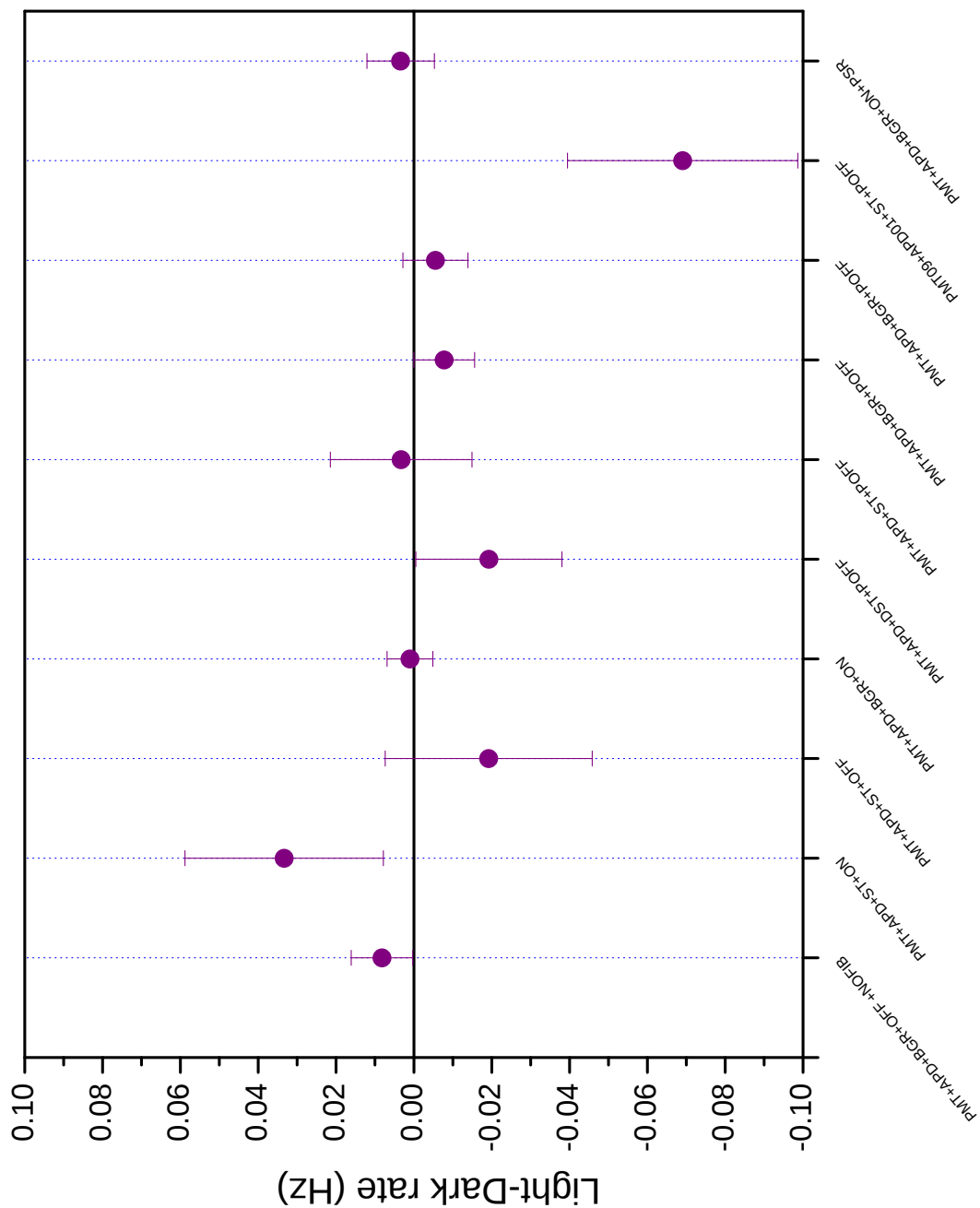


Figure 4.12: Difference between light and dark counts for the measurements done with the G-APD. Error bars correspond to 1σ errors.

field during the background runs. Two dummy solar tracking were done to check that there is no influence on the sensor noise from the magnetic field or the magnet movement. The switching frequency was fixed at 1 Hz for all the measurements.

All the runs show a similar background and no excess of counts are visible. There are however two exceptions where the noise level is higher:

1. The measurements highlighted in the yellow circle were done with the magnetic field on after a long time it was kept switched off. Both light and noise level are higher than the runs done before and after. This could be ascribed to noise coming from the magnet since it had not yet reached a stable condition, or to an increase in ambient temperature and consequently in the sensor temperature. Despite the increase in overall count rate the difference between light and dark counts was not affected by this source of noise.
2. The last solar tracking, highlighted with the blue circle, shows a difference between light and dark counts, which is however within 1σ . This last tracking was done, as the previous one, with the magnet pointing off center of the Sun. For the first half of the measurement the magnet pointed 0.25° to the left of the center of the Sun, while for the other half it pointed 0.25° to the right. The higher solar activity in this region has motivated this kind of measurements.

The difference between light and dark count rates for the February-March 2008 data is shown in fig.4.14 with 1σ error bars. As in the previous measurements done in November 2007 no signal over background is present. The average dark count rate measured during background runs is:

$$\text{DCR} = 0.37 \pm 0.06 \text{ Hz} \quad (4.10)$$

while the average light count rate measured during "live" solar tracking is:

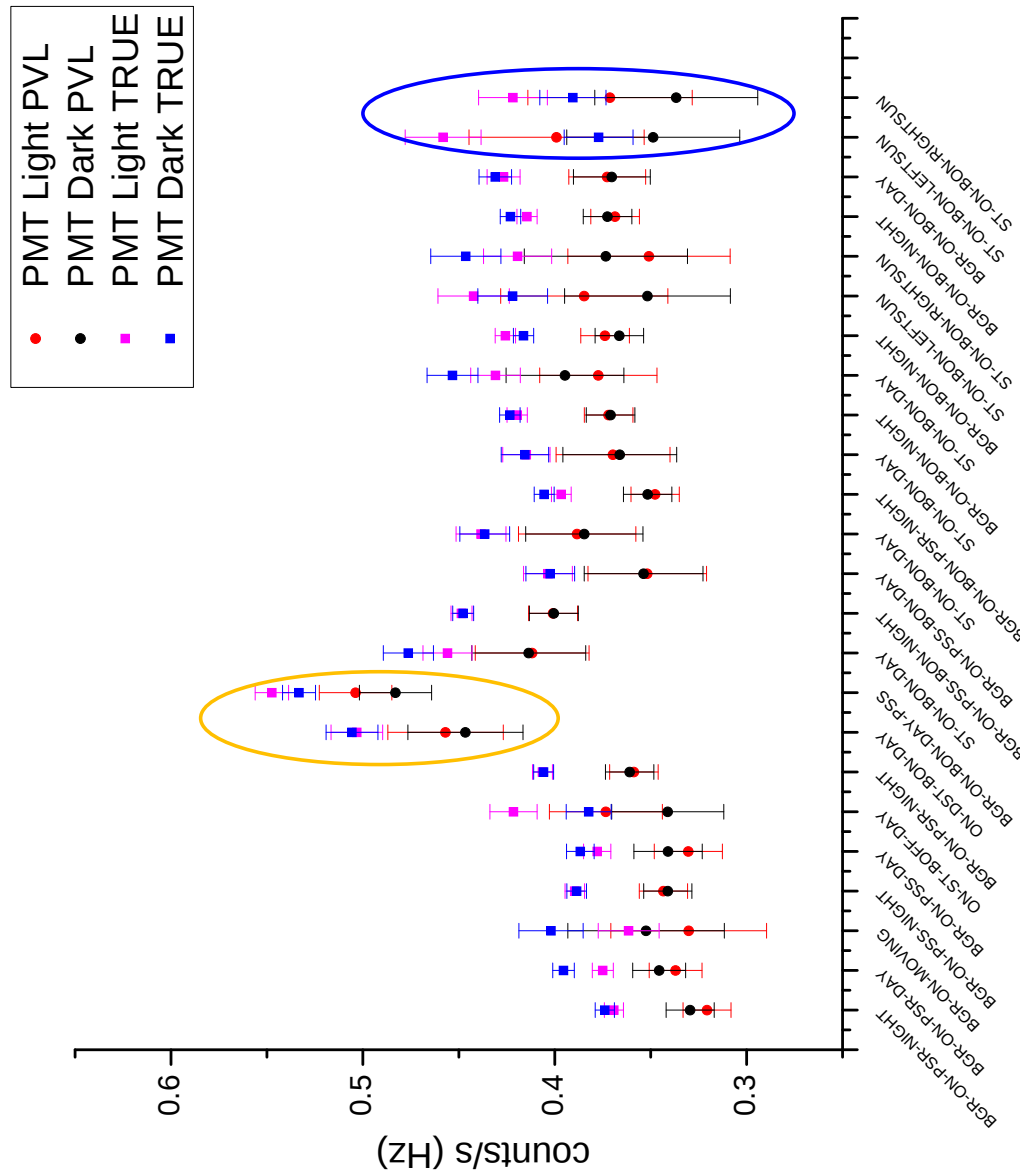
$$\text{LCR} = 0.39 \pm 0.05 \text{ Hz}. \quad (4.11)$$

The corresponding background count rate is compatible with the one measured in absence of solar tracking. The runs done during the dummy solar tracking are not taken into account. The mean dark and light count rates when the magnet was pointing to the left of the Sun are:

$$\begin{aligned} \text{DCR}_{\text{Left}} &= 0.35 \pm 0.04 \text{ Hz} \\ \text{LCR}_{\text{Left}} &= 0.39 \pm 0.04 \text{ Hz} \end{aligned} \quad (4.12)$$

while the rates when the magnet is pointing to the right of the Sun are:

$$\begin{aligned} \text{DCR}_{\text{Right}} &= 0.35 \pm 0.04 \text{ Hz} \\ \text{LCR}_{\text{Right}} &= 0.36 \pm 0.04 \text{ Hz}. \end{aligned} \quad (4.13)$$



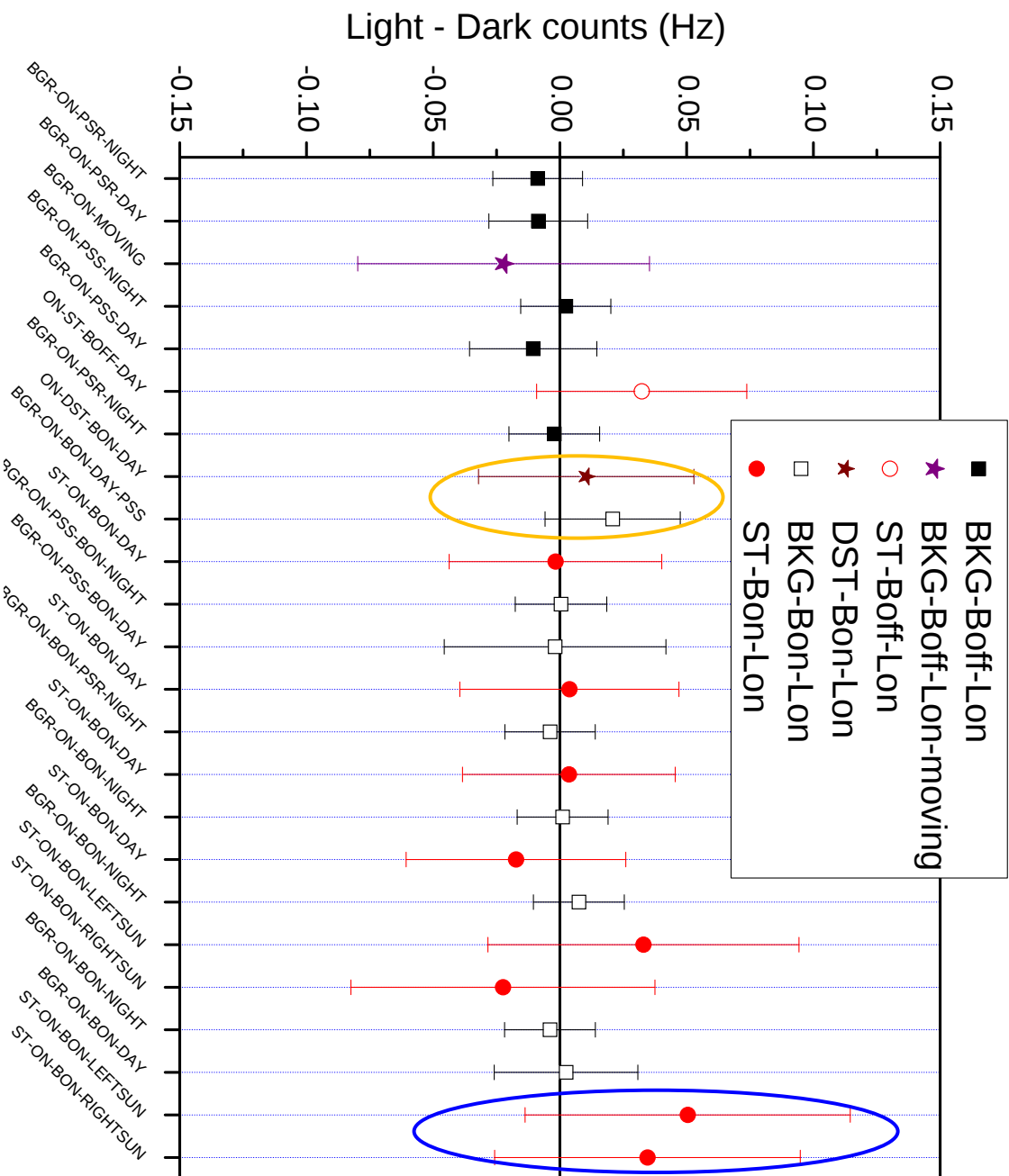


Figure 4.14: Difference between light and dark count rates for the different types of measurements done during February-March 2008. The error bars corresponds to 1σ errors. Different symbols were used for the different type of measurements (see legend). The yellow circle highlights the measurements done with the magnetic field on after a long time it was kept switched off. The blue circle highlights the last solar tracking done with the magnet pointing off center of the Sun: 0.25° to the left (LEFTSUN) and 0.25° to the right (RIGHTSUN). See text.

4.5 Conclusions

A total of about 16 hours of "light" data and a total of about 150 hours of background data with different ambient conditions have been taken during the two measurement campaigns at CAST. The total average dark count rate for the photomultiplier tube obtained during the measurements taken in February-March 2008, in which the same conditions were present, is:

$$DCR = 0.37 \pm 0.06 \text{ Hz.} \quad (4.14)$$

This rate is compatible with the one measured in the preliminary tests in the Trieste laboratory and with the one measured during November 2007. The sensitivity of the PMT sensor can be evaluated following the equation:

$$SNR = \frac{\nu_{light}}{\sqrt{2 \left(\frac{\nu_{light} + 2DCR}{\tau} \right)}} \quad (4.15)$$

where SNR is the signal to noise ratio, ν_{light} is the rate of arrival of the signal photons in Hz and τ is the total acquisition time in seconds. Assuming $SNR = 1$, a global detector efficiency ε of 4% (the product of the telescope collection efficiency, 50%, and the detector quantum efficiency which has the value of 8% at 530 nm) and a total acquisition time of 100 hours, the minimum rate of arrival of photons to which one is sensitive is:

$$\nu_{light} = \frac{1}{\tau \varepsilon} (1 + \sqrt{1 + 4\tau DCR}) = 0.05 \text{ Hz.} \quad (4.16)$$

In order to increase the sensitivity by a factor of 10 the integration time should be 100 times longer, which means at least 5000 days of running, since each run lasts 1 hour and half. Another way to improve the sensitivity is to use a detector with a lower background, sensitive to single photons, and with a high quantum efficiency. An improvement of a factor 100 in detector background and of a factor 2 in the detector efficiency has the same effect as increasing 100 times the integration time. The types of detectors which, at this moment, could satisfy these requirements are:

1. Transition Edge Sensor (TES). It has a very low background (in the mHz range) and a good sensitivity up to few eV, but a very small active area ($25 \mu\text{m} \times 25 \mu\text{m}$). It also needs to be operated at very low temperatures (100 mK);
2. Depleted P- Channel Field Effect Transistor (DEPFET). It has a low background and could be used for spectroscopic purposes. On the other hand it has a good efficiency in the few keV range and less in the eV range;
3. Liquid Nitrogen cooled G-APD ($LN_2G - APD$). It has a high efficiency (up to 50%) in the eV range. It is reasonably easy to use and has a low background provided a

suitable correction for the afterpulsing effect is applied. The detector area is small, but could be increased if a matrix configuration is used, at the expenses of a higher background.

The final choice, for the future progress, fell on the cooled G-APD. The sensor itself is commercially available, while a liquid nitrogen cryostat was built in the Trieste laboratory. The preliminary studies on this kind of detector are presented in the next chapter.

4.5.1 Limit on $g_{a\gamma\gamma}$

With the background level measured during the campaigns at CAST a limit on the coupling constant between axions and photons can be set by assuming a standard solar axion model and by considering the integral of the expected solar axion flux in the visible range (0-4 eV).

The number of expected photons is defined as:

$$\begin{aligned}\nu_{light} &= \phi_{visible} P_{a\gamma} A \\ &= 5 \cdot 10^{-24} g_{a\gamma\gamma10}^4,\end{aligned}\tag{4.17}$$

where $\phi_{visible}$ is $1.68 \cdot 10^2 \cdot 10^{-10} \cdot g_{a\gamma\gamma10}^2$, $P_{a\gamma}$ is $2 \cdot 10^{-17} \cdot g_{a\gamma\gamma10}^2$, and A is the magnet bore cross section equal to 14.5 cm^2 . Using $\text{DCR} = 0.37 \text{ Hz}$, $\tau = 100 \text{ hours}$ and a signal to noise ratio equal to one gives:

$$g_{a\gamma\gamma} < 3 \cdot 10^{-5} \text{ GeV}^{-1}\tag{4.18}$$

which is distant from the region obtained with the CAST X-ray detectors. However, this is just a theoretical calculation since the expected photon flux at low energies is not known. As introduced in chapter 1 it could be enhanced by a low-energy axion production in the solar corona, or it could be reduced by other processes. This shows the importance of studying this region of the reconverted spectrum to shed light on the solar axion production mechanism.

Chapter 5

Development: a Liquid Nitrogen cooled G-APD

The need for a low background detector, to improve the sensitivity in the low-energy range for WISP search experiments, was pointed out in the previous chapter. The detector chosen for the initial development is a Geiger mode avalanche photodiode cooled at liquid nitrogen temperature. The use of a G-APD instead of a PMT seems, in fact, very promising since, as shown in chapter 3, these sensors are compact, insensitive to external magnetic fields, have a higher quantum efficiency in the visible range and they need a relatively low voltage supply to reach the same gain as a PMT.

The first tests were started with a model id101-50 sensor made by idQuantique. It has an active area diameter of $50\text{ }\mu\text{m}$ and a dark count rate at room temperature in the range of 2-10 kHz. The sensor, shown in fig.5.1, is equipped with an on-chip active quenching circuit and a ThermoElectric Cooler (TEC) on which the silicon sensor is mounted. A thermistor placed closed to the TEC is used to monitor the sensor temperature. Everything is encapsulated in a TO-5 standard package with eight output pins (see fig.5.2). These are designed to supply the bias voltage, the TEC current, to check the sensor tem-

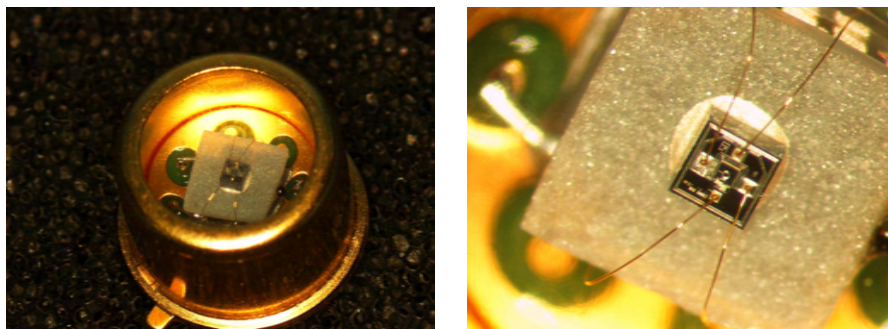


Figure 5.1: *Left:* photograph of the mod.id101-50 sensor made by idQuantique. *Right:* a close-up of the silicon chip and of the thermoelectric cooler.

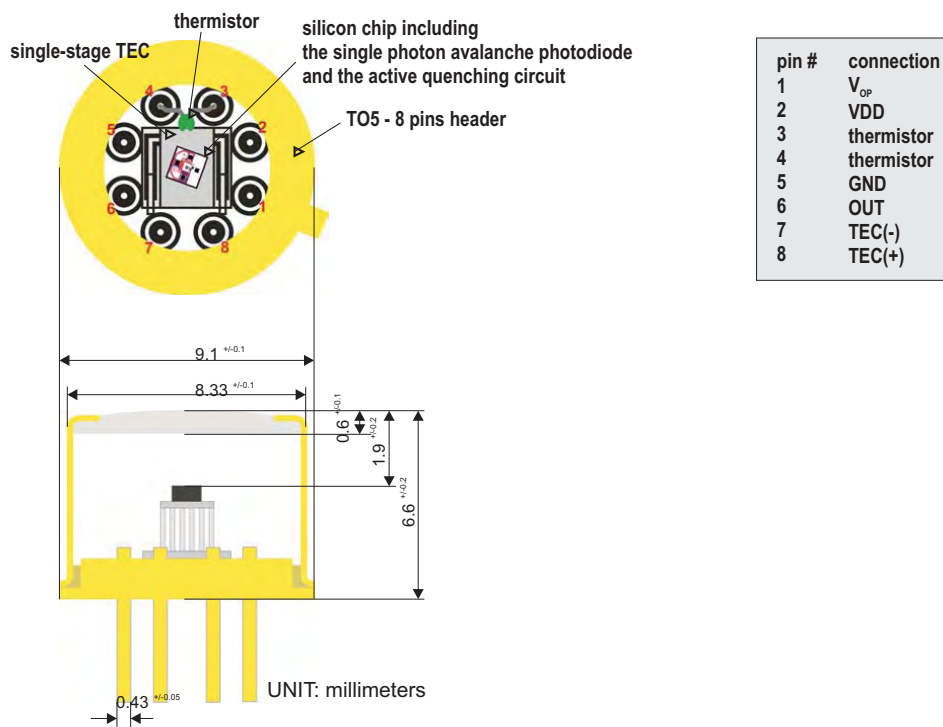


Figure 5.2: Mod.id101-50 main parts. The pin connections are also indicated. Figure taken from[73].

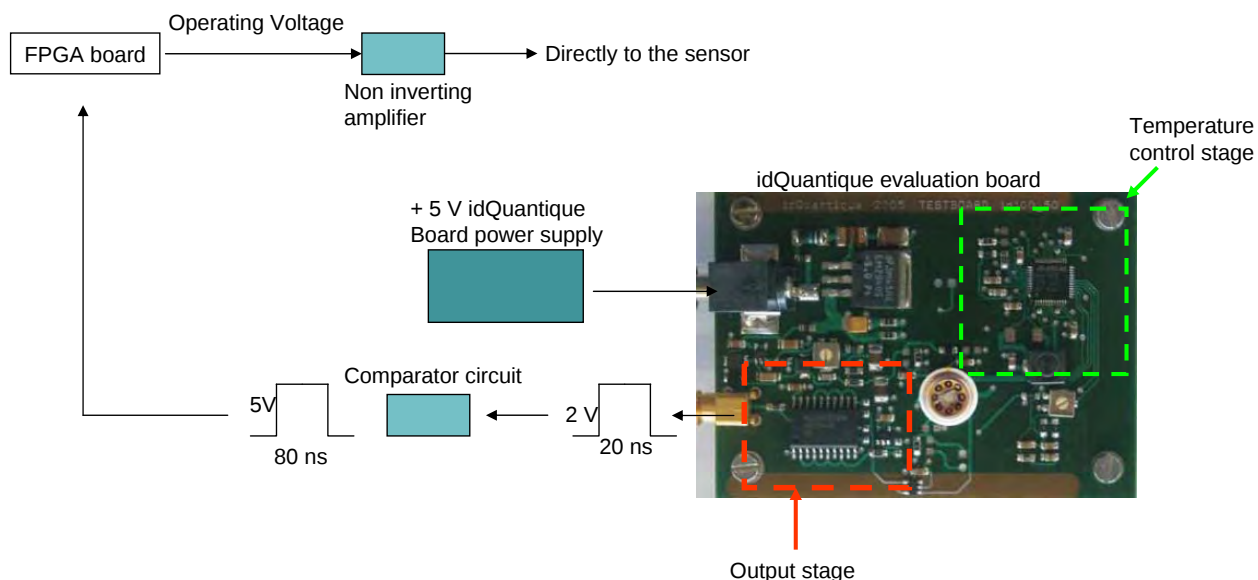


Figure 5.3: Scheme of the circuit used for the low temperature and test measurements with the mod.id101-50 sensor. The main components are the power supply stage, the output stage and the temperature control stage (used only for the preliminary tests). The preliminary output stage and the temperature control stage are integrated in the idQuantique evaluation board.

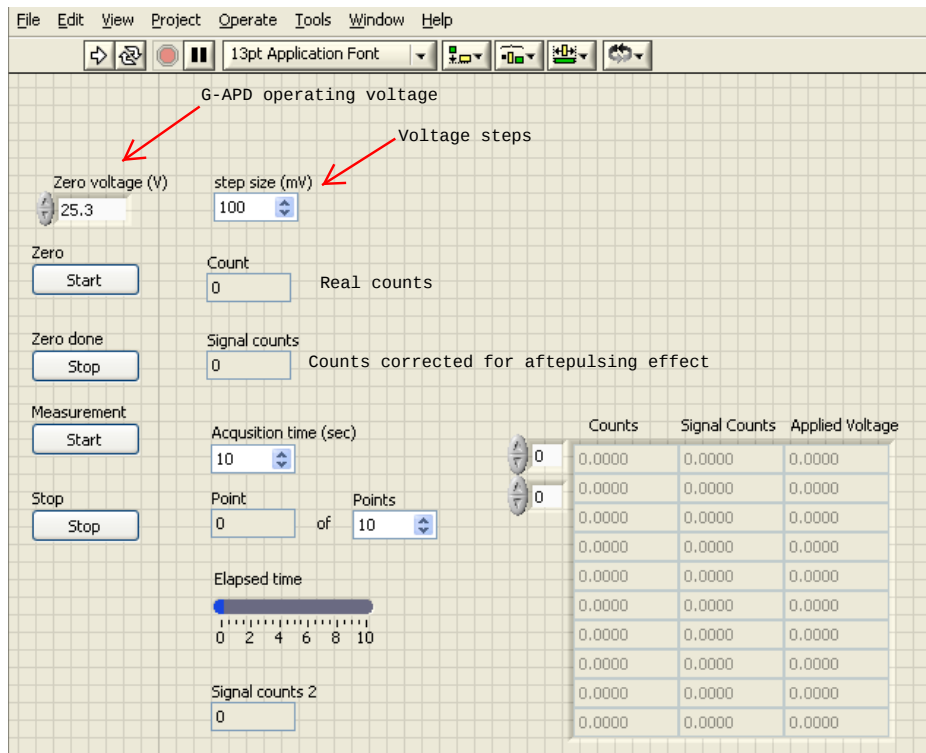


Figure 5.4: Screen shot of the software controlling the mod.id101-50 power supply. The actual output voltage is a factor 3 lower than the inserted one. The voltage is then amplified by a factor 3 by a non inverting amplifier. This is necessary since the FPGA maximum output voltage is 10 V, while the id101-50 operating voltage can reach 30 V.

perature and to read the output signals. The electronic circuit used for low temperature measurement is schematically shown in fig.5.3. The main parts of the sensor front-end are summarized below.

Power stage: The operating voltage, $-V_{op}$, is supplied independently with respect to the 5V sensor drive voltage, since it strongly depends on the working point temperature. The V_{op} voltage ranges between -28 V to -15 V and is supplied by a mod.7831/R FPGA board (National Instruments) and controlled by a software developed in Labview (see fig.5.4 for a screen-shot). The FPGA output voltage is amplified by non-inverting amplifier circuit, which also prevents supplying a positive bias voltage to the detector. The operating voltage is changed according to the sensor temperature in order to operate in the same excess voltage conditions (see section 5.14). Following the manufacturer indications, the excess voltage must be at most 5V larger than the breakdown voltage, which depends on temperature.

Temperature control stage: this part of the evaluation board circuit is used only during the preliminary tests. Once the working temperature is determined, an appropriate

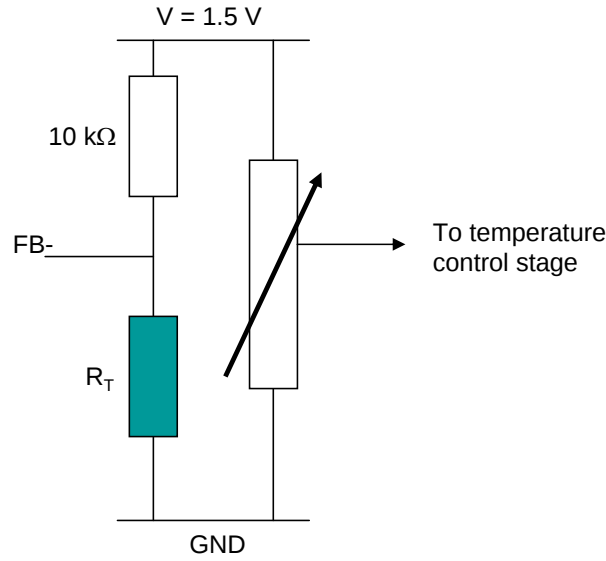


Figure 5.5: Temperature control circuit. The FB- voltage value can be adjusted acting on the potentiometer indicated. *See text.*

current is supplied to the Peltier module. The sensor temperature is controlled by a thermistor R_T which has a resistance increasing as the temperature decreases:

$$R_T = R_{293} e^{\beta(293-T)/(293 \cdot T)} \quad (5.1)$$

where β is the thermistor constant (equal to $2918.9 \pm 5\%$ K) and R_{293} is the value of the resistance at room temperature ($R_{293} = 2.2 \pm 0.6$ kΩ). The temperature is controlled by the circuit shown in fig.5.5. A potentiometer allows one to select the value of the FB- voltage according to the relation:

$$FB- = \frac{V_{ref} R_T}{10 \text{ k}\Omega + R_T}. \quad (5.2)$$

Once the value is selected a feedback circuit keeps the detector temperature in that range.

Output stage: the output signal from the active quenching comparator circuit is shaped using the circuit described in section 3.2.9. The 2 V output signal is then again shaped to give a standard TTL signal by a second comparator circuit built in our laboratory.

Although the sensor is designed to be operated at a minimum temperature of -40°C the goal of the work presented here is to see how the sensor performs at even lower cryogenic temperatures. In particular, the behavior of the dark count rate and of the quantum efficiency are investigated.

Recent experimental studies (see next section) showed that is possible to cool Geiger mode avalanche photodiodes at liquid xenon (-80°C) and liquid nitrogen (-197°C) temperatures without a significant loss of performances.

5.1 Theory of low temperature G-APDs

In the last few years, the use of Geiger mode avalanche photodiodes cooled at cryogenic temperatures has increased[76, 77], reaching a lower background at the price of a small loss in quantum efficiency. Furthermore, at low temperatures, the bias voltage needed to have a high gain is reduced. On the other hand, a reduction in temperature will increase the afterpulsing effect, thus worsening the background. The chosen operating temperature of the sensor is then normally a compromise among gain, dark count rate, quantum efficiency, and afterpulsing effects. Let us briefly consider each one of these elements.

5.1.1 Gain

The gain of G-APDs increases as the bias voltage increases[78] and, being the excess voltage above breakdown kept fixed, the gain of the detector does not change with temperature. The detector gain follows the equation:

$$G = \frac{C}{e}(V_{op} - V_{bd}), \quad (5.3)$$

where e is the elementary charge, C is the total sensor capacitance, V_{op} the bias voltage and V_{bd} the breakdown voltage. Lowering the temperature has the consequence of slightly decreasing the sensor capacitance, while, on the other hand, increasing the quenching resistance. The product of the quenching resistance and of the sensor capacitance gives the dead time, or recovery time, of the detector. Lowering the temperature will thus increase the recovery time, diminishing the response efficiency at high count rates. This drawback loses importance when the sensor is operated in single photon mode in experiments where one has a low rate of expected signal photons.

5.1.2 Breakdown voltage

The breakdown voltage of an avalanche photodiode depends on the mobility of the carriers, thus it changes as the temperature changes. Increasing the temperature has the consequence of increasing the lattice vibrations in the substrate material, which will

in turn decrease the carrier mobility. A higher voltage is then required to create an avalanche. On the other hand, at low temperatures the lattice vibrations are reduced and so are the thermally generated carriers, thus, due to less scattering, a lower bias voltage is needed to create an avalanche. The dependence of the bias voltage on the sensor temperature is usually linear, with a slope depending on the substrate material and purity level.

5.1.3 Dark count rate

The expected dark count rate of G-APD sensors cooled at cryogenic temperatures follows both a Poisson distribution for the primary carriers and a conditionally Poisson distribution for the trapped carriers which induce secondary events (afterpulsing effect). The primary carriers are emitted both by thermal excitations and by tunneling effects. The probability of exciting a primary carrier is expressed by the relation (see equation 3.15):

$$P_{thermal}(T) \propto T^{3/2} e^{-E_g/2k_B T},$$

where E_g is the band-gap energy and k_B the Boltzmann constant. $P_{thermal}$ depends strongly on the temperature. The theoretical curve of the thermally generated dark counts as a function of the sensor temperature is shown in fig.5.6. A decrease of a factor of 10^4 is expected at 200 K[79]. At lower temperatures, the dominant effect is the tunneling across the valence and conduction bands. The tunneling effect depends only on the over-voltage, V_E , while it is independent of the temperature, even if its effect is visible only at very low temperatures where the other contributions disappear.

Another important element to consider when going to cryogenic temperatures is the maximum excess voltage allowed. If the over-voltage is, in fact, too high the multiplication factor greatly increases and the dark count rate first rises exponentially and then, a few millivolts later, drops to zero. The exponential increase is also present at room temperature, but it is masked by the high background. At lower temperatures, due to the lower background, it is clearly evident and is caused by the higher mobility of the free carriers.

5.1.4 Afterpulsing

A feature that must be taken into account when cooling G-APD detectors is the rapid increase of afterpulsing events. At cryogenic temperatures there could be up to a thousand of afterpulses following a single event, due to the increase of the trapping probability while decreasing temperature. The number of deep level traps which, due to the lower

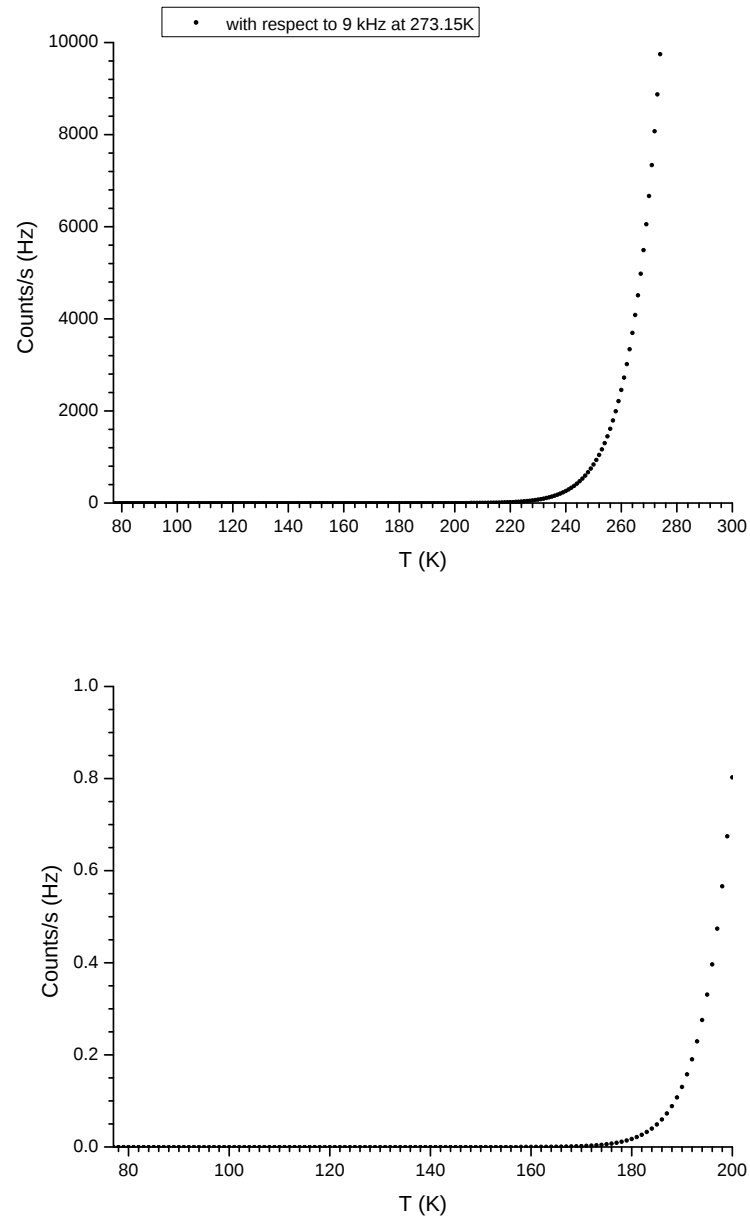


Figure 5.6: *Top:* Theoretical curve of the dark count rate as function of the detector temperature considering only thermally emitted carriers. The count rate is referred to 9 kHz DCR at 273.15 K. The curve is plotted in the range 80-300 K. *Bottom:* zoom of the previous curve in the range 77 - 200 K. A decrease of a factor 10^4 is expected already at 200 K. See text.

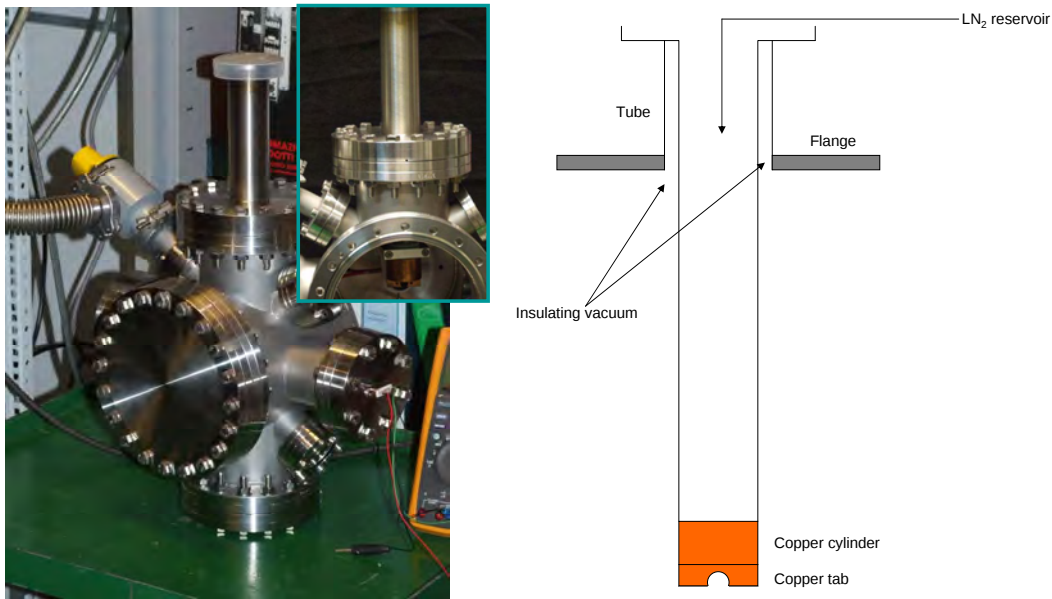


Figure 5.7: *Left:* photograph of the vacuum chamber with the cold finger inserted in it. The cold finger is a 15 cm long tube with a copper cold ring welded on the bottom. The other end of the tube is welded to the entrance flange in order to be isolated from the environment. *Right:* schematic cross section of the cold finger assembly.

lattice vibrations, are released at delayed times with respect to the avalanche triggering event, is in fact larger at lower temperatures.

5.2 Liquid Nitrogen Cryostat

The mod.id101-50 sensor is cooled at liquid nitrogen temperature by contact with a cold finger, built at the INFN section of Trieste, inserted in a vacuum chamber (see fig.5.7).

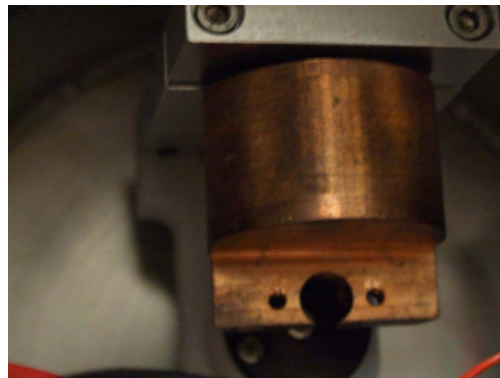


Figure 5.8: Detail of the copper vessel and of the cold finger. The sensor holder tab is shown.

Material	Use	Thermal expansion coefficient
stainless steel	flange and cold finger	$17.3 \mu\text{m} / \text{m}^\circ\text{C}$
Copper	cold finger vessel and holder tab	$17.7 \mu\text{m} / \text{m}^\circ\text{C}$
BK7 glass	focussing lens	$7.10 \mu\text{m} / \text{m}^\circ\text{C}$
kovar	TO-5 sensor header	$7.10 \mu\text{m} / \text{m}^\circ\text{C}$
polyethylene	lens and fiber holder	$62.0 - 87.0 \mu\text{m} / \text{m}^\circ\text{C}$

Table 5.1: Thermal expansion coefficients of the different materials used in the construction of the cold finger.

The cold finger, shown in fig.5.7, is a 15 cm long steel tube with a 5 cm long hollow copper cylinder welded at his end. The bottom of the copper cylinder ends with a 2 cm high copper tab (fig.5.8), where the detector is placed. A hole with diameter 0.1 mm larger than the detector case diameter, is pierced on the tab. This avoids mechanical stresses of the sensor while lowering the temperature. The choice of materials was done according to their thermal expansion coefficients (see table 5.1), thus minimizing movements or misalignments when the finger is filled with liquid nitrogen. The cold finger is, at the top end, welded to a flange as shown in fig.5.7 at right. The flange then is bolted onto a vacuum chamber, which is evacuated down to 10^{-3} mbar using a membrane pump. This chamber has also feedthrough ports for electrical signal and power supply cables, for thermocouple cables and for an optical fiber. The temperature of the cold finger and detector enclosure are monitored by two thermocouples placed on the copper cylinder and on the copper tab near the TO-5 header. Their voltage output signal is acquired by a National Instruments mod.CRIO 9215 board and converted in temperature values by a Labview software (a screen-shot is shown in fig.5.9). The temperature of the sensor is also monitored by using the on-chip thermistor and by checking FB-. Unfortunately, at around 180 K, the resistance of the thermistor becomes of the order of a G Ω and thus it can no longer be used. In addition, the vacuum chamber temperature is monitored using an external thermocouple sensor. When the cold finger is filled with liquid nitrogen the chamber temperature does not change with respect to the laboratory room temperature, thus confirming a sufficient level of insulating vacuum, also monitored by a Pirani type gauge installed on one of the chamber flanges. Without the pumping on a good level of vacuum is maintained inside the cryostat for about 2 hours. A few tests made on the detector background with the pumps on and off showed no difference in the acquired counts, thus the pumping system can be left on during the measurements. For what concerns the temperature, the cryostat needs about 30 minutes to reach liquid nitrogen temperature, starting from room temperature, while being continuously filled. Once the thermal equilibrium is reached, the temperature of -180°C is kept at least for one hour and a half without the need of refilling. When the liquid nitrogen has evaporated com-

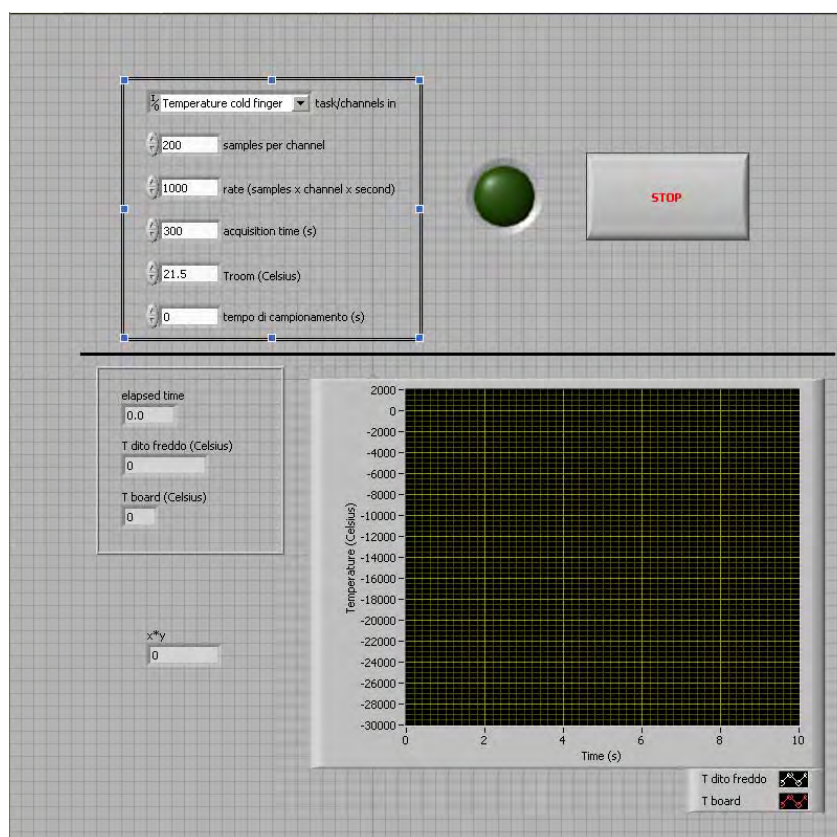


Figure 5.9: Screen-shot of the Labview developed software for the reading of the thermocouples. The thermocouple output voltage signal is converted into a temperature value by the software itself.

pletely the temperature starts to rise exponentially (see fig.5.10). Usually twelve hours are needed to reach room temperature again. This period however could be shortened by attaching a resistor on the cold finger and passing a current through it to heat it up. The warm-up time depends also strongly on the detector being placed in the copper tab or not. With the id101-50 in place, in fact, due to the wire connections for the power supply and the output signal, the time is shortened since heat is lost also through the wires. The power supply circuit is placed outside the vacuum chamber and it is connected to the sensor pins through an electrical feedthrough. In order to avoid loss of information the output signal shaping circuitry is placed inside the cryostat.

5.3 Focussing system

The detector is connected to the light source by an optical fiber and a focussing system (see fig.5.11). The focussing system uses a 0.5" diameter visible achromatic doublet

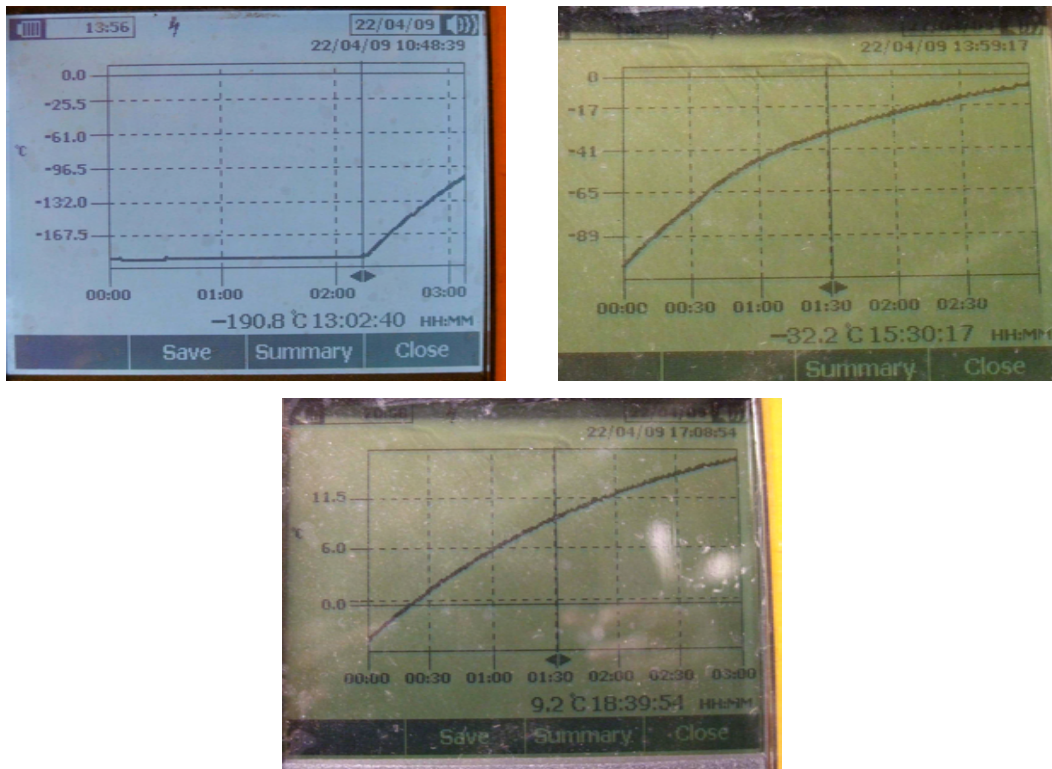


Figure 5.10: Measured plots of the cold finger temperature as a function of time showing the exponential growth when the liquid nitrogen filling stops.

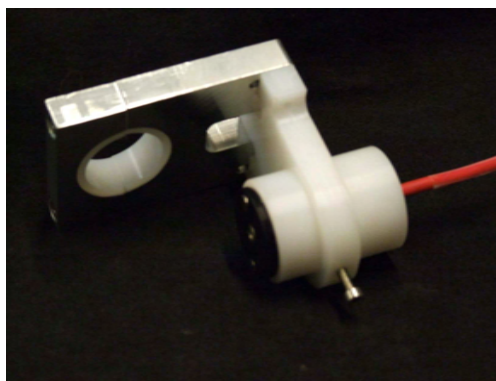


Figure 5.11: Photograph of the focussing system for the cold finger setup. The structure of the lens and fiber holder is made of polyethylene to prevent freezing. The system is mounted directly on the cold finger.

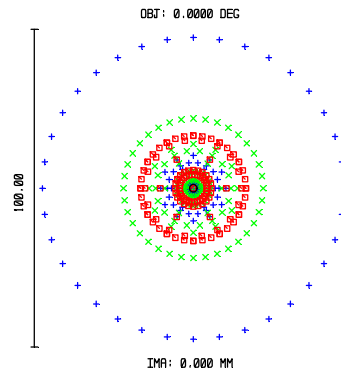


Figure 5.12: Theoretical dimensions of the light spot in the lens focus (different colors refer to the different wavelengths). Figure taken from [80].

placed in a polyethylene mount to avoid freezing problems, since it is very close to the cold finger. The focus of the lens is 15.7 mm away from the lens surface, here the spot diameter should be $40\mu\text{m}$, well within the detector active area diameter (see fig.5.12). The lens holder can be moved back and forth to focalize on the detector.

5.4 Signal acquisition software

A screen shot of the acquisition software used with the G-APD was already shown in fig.5.4. It has 5 main functions.

1. Supply the operating voltage to the sensor. The voltage can be selected in the range from 0 to -30 V.
2. Acquire the G-APD output signals.
3. Correct the G-APD output signals for the afterpulsing effect (see sec.5.7).
4. Set the acquisition time.
5. Scan the voltage region around V_{op} , with a selectable voltage step (usually 100 mV), to find the correct working voltage as the temperature changes.

5.5 Breakdown voltage and temperature

Two test detectors were used in order to study their performances when cooled at cryogenic temperatures. Both detectors are made by idQuantique, but present different

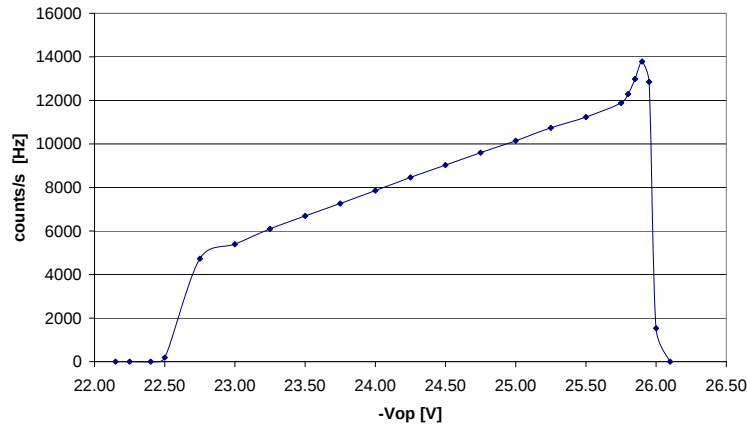


Figure 5.13: Typical curve obtained for the dark counts as function of the applied bias voltage, V_{op} . The curve plotted here is measured for the id1 detector at 0°C . (See text).

backgrounds rates: one has 9 kHz of dark count rate at 0°C , while the other has a little lower background rate of 5 kHz at the same temperature. In the following paragraphs they are referred to as id1 and id2, respectively.

For both detectors the relation between breakdown voltage and working point temperature has been studied. The temperature is changed in steps of $5\text{-}10^\circ\text{C}$ in the range $-20^\circ\text{C} \rightarrow 25^\circ\text{C}$, acting on the Peltier element current, and then also the point at -196°C is measured. For each temperature step the operating voltage, V_{op} , is changed in the range from -17 V to -28 V and the corresponding dark count events are acquired for 20 seconds. Even if 20 seconds are enough to reach the thermal equilibrium, a one minute pause is taken before each measurement in order to allow the detector to stabilize. A typical curve obtained with this method is shown in fig.5.13. To obtain the *voltage vs temperature* curve two voltage points are taken as reference: the breakdown voltage, V_{bd} , and the peak voltage, V_{peak} . The breakdown voltage is taken at the point where the counts start to rise, where $V_{bias} - V_{bd} = 0$, and the counts return again to zero about 4V after this point. The peak voltage, instead, is considered at the point where counts, dark and light, grow exponentially, usually after voltage $V = V_{bd} + 3.75\text{V}$.

The measured *voltage vs temperature* curves are shown in fig.5.14 for the two detectors. The points follow a linear trend with equation:

$$\begin{aligned} V_{BD} &= 26 \left[\frac{\text{mV}}{^\circ\text{C}} \right] T + 22.39 \text{ V} \\ V_{peak} &= 24 \left[\frac{\text{mV}}{^\circ\text{C}} \right] T + 26.07 \text{ V} \end{aligned} \quad (5.4)$$

for the id1. If this linear trend is valid also for low temperatures then the breakdown voltage expected at -196°C is -20 V . However the value actually measured is higher, and if the measured slope is used it corresponds to -150°C . It is possible, in fact, that the sensor

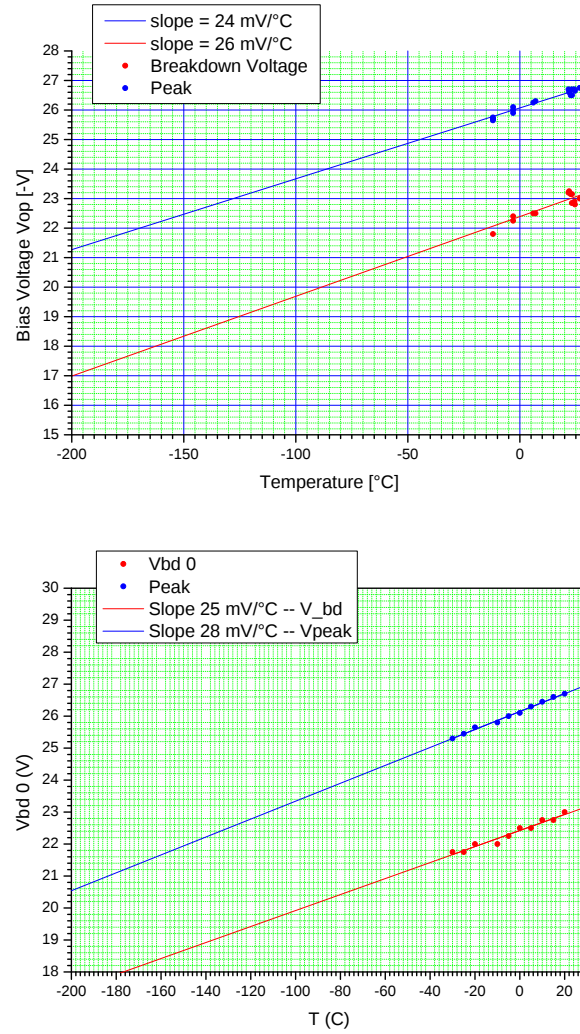


Figure 5.14: Breakdown and peak voltage as function of the temperature (*see text*). Data are taken for id1 (top graph) and for id2 (bottom graph).

has not reached the liquid nitrogen temperature due to a poor heat transfer between the sensor chip and the ceramic thermoelectric cooler. Unfortunately at this temperature the thermistor does not work and a direct check of the sensor temperature was not possible.

5.6 Detector Efficiency

The total efficiency of the detector is defined as the product of the sensor quantum efficiency and of the geometrical efficiency. The first one depends on temperature, voltage and active area. For what concerns the voltage dependence, the detector efficiency

increases as the bias voltage increases since the sensor gain is higher, however also the background of the detector will rise and a compromise between the two must be reached. The geometrical efficiency instead depends on the focussing system, on the fiber numerical aperture and on the ratio between the spot area and the APD active area. From this point of view, the focussed spot diameter must be smaller than $50\text{ }\mu\text{m}$ to avoid loss in efficiency.

The goal is to limit the loss in quantum efficiency of the detector when cooled with liquid nitrogen. Several measurements were performed with the sensor at different temperatures, such as room, ice, standard TEC zero degrees and liquid nitrogen, all at a fixed intensity of illumination. The illuminating beam is realized with a blue led encapsulated in a black tube and connected to a $600\text{ }\mu\text{m}$ core diameter multimode test fiber. The fiber is then placed in front of the G-APD, actually a few centimeters away, in order to completely cover the active area. The LED luminosity is then changed in order to have different light intensities. Measurements at room temperature are carried out first. These are the reference points for the low temperature acquisitions. The sensor bias voltage is varied from -18 V to -28 V and the corresponding counts are acquired for 10 seconds with the LED on and for 10 seconds with the LED off. Once the measurement at room temperature is completed, the one at 0°C is immediately done with the same procedure, and so on for all the temperatures of interest. The measured on and off curves at 0°C are shown in fig.5.15 along with the point by point LED on-LED off difference, which gives the actual counts at that voltage. Fig.5.16 shows the comparison plot for a led emission rate of $1.4 \cdot 10^3\text{ photons/s}$, while fig.5.17 is relative at a rate of $4 \cdot 10^3\text{ photons/s}$. The three temperatures of 20°C , 0°C and LN_2 were investigated. In the case of LN_2 temperature, the cold finger temperature was actually -180°C while the sensor was at -150°C . Since from the manufacturer specifications the working voltage, at zero degrees, is -25.3V , which is just below the exponential growth region, 4 V away from the breakdown voltage, it has been decided to keep the same overvoltage for all the measurements to define a working region (highlighted with a box in fig.5.16 and 5.17). Once the supply voltage was defined the number of counts was taken. From the plots one sees that there is no significant loss in efficiency between 0°C and LN_2 . This result confirms the possibility of cooling down the detector without significative changes in its behavior.

5.7 Afterpulsing effect

The afterpulsing problem has been described in section 3.1.11. Although it is in practice negligible at room temperature, it becomes very important at low temperatures for Geiger mode avalanche photodiodes. Lowering the temperature, in fact, increases the entrapment time, τ_d , or the time at which the field assisted thermal excitation will depop-

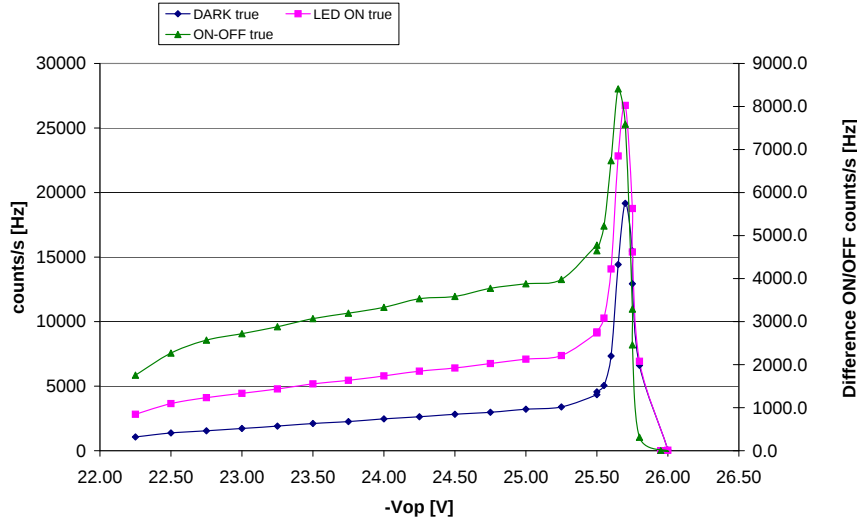


Figure 5.15: Typical curve obtained at zero degrees for the light and dark counts as a function of the bias voltage. The green line is the point by point difference between signal and background. The curve is obtained by changing the operating voltage when the detector is illuminated by a blue led light excited at 4 kHz.

ulate these states:

$$\tau_d = \frac{1}{\sigma v N} e^{E_a/kT} \quad (5.5)$$

where T is the temperature, σ is the trapping cross section, $v=v(T)$ the average thermal velocity of the carriers to be trapped, E_a is the activation energy of the primary trap, and $N=N(T)$ is the effective density of states of the relevant band (conduction band for the electrons traps and valence band for the hole traps). Assuming $v \propto T^{1/2}$ and $N \propto T^{3/2}$, the overall temperature dependence of τ_d is:

$$\tau_d \propto \frac{1}{T^2} e^{E_a/kT} \quad (5.6)$$

and the afterpulsing contribution to the total dark count rate is:

$$P_a \frac{N_{ft}}{\tau_d} e^{-\frac{t+t_{ho}}{\tau_d}} \quad (5.7)$$

where P_a is the probability that a single carrier generates an avalanche, N_{ft} is the number of filled traps and t_{ho} is the hold-off time required to rearm the G-APD after an avalanche. At -180°C the afterpulsing effect is very important and for one single photon count a total of 500 up to 1000 afterpulses might be present. This number depends also on the frequency of arrival of photons: as it increases the number of afterpulses increases. To overcome this problem in practice, it was decided to increase the dead time of the detector up to 100 ns, instead of the normal 40 ns and to reject pulses that occur closer in time than the sensor dead time. This was done by modifying the acquisition software, which

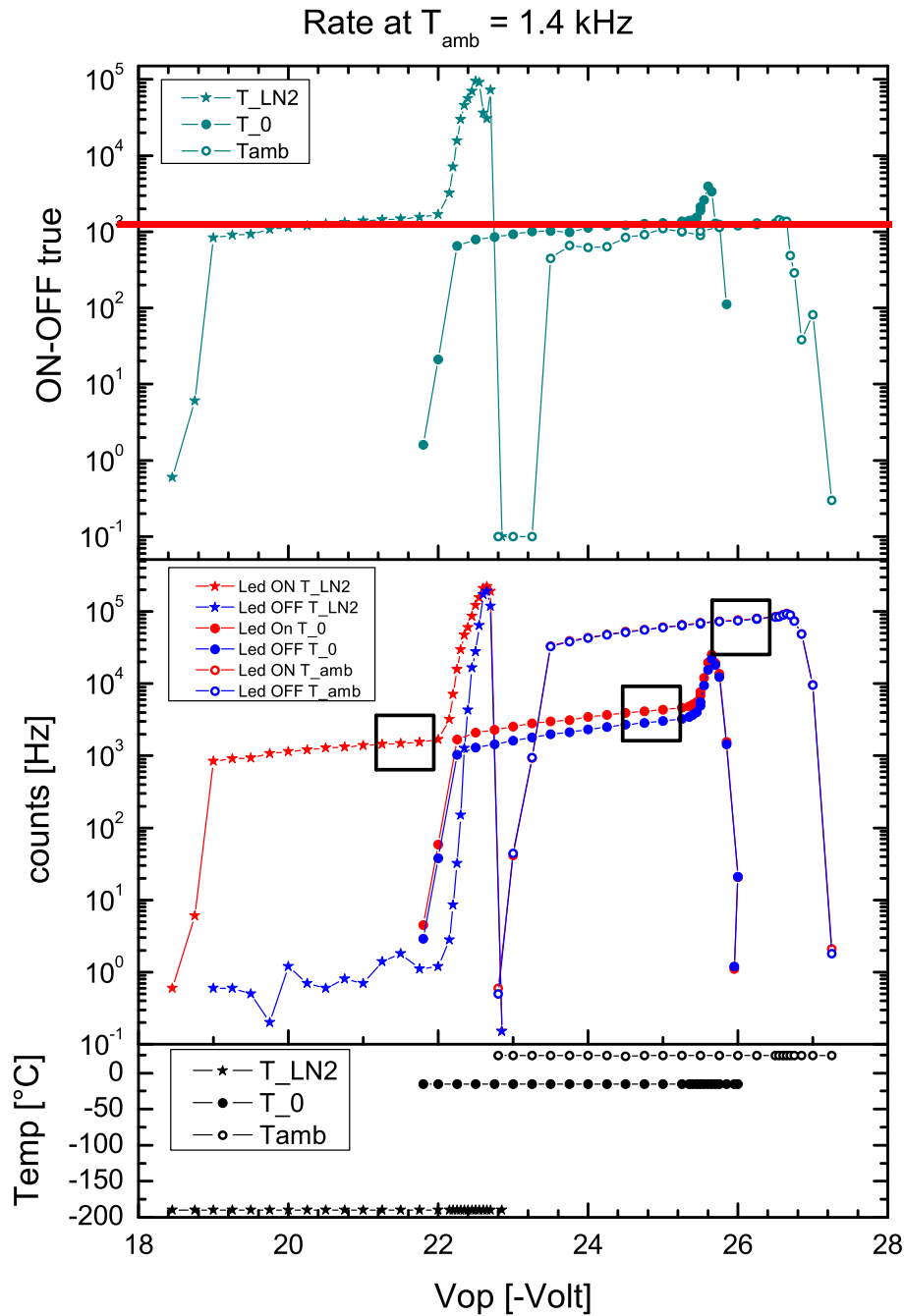


Figure 5.16: Comparison plots at three different temperatures for the id1 sensor. *Bottom:* measured cooling temperatures. *Middle:* acquired background and light data for each temperature as a function of the operating voltage. *Top:* point by point difference between light and dark counts for a blue LED emitting at 1.4 Hz. The working regions are indicated with boxes, while the red line indicates the expected counts. (See text).

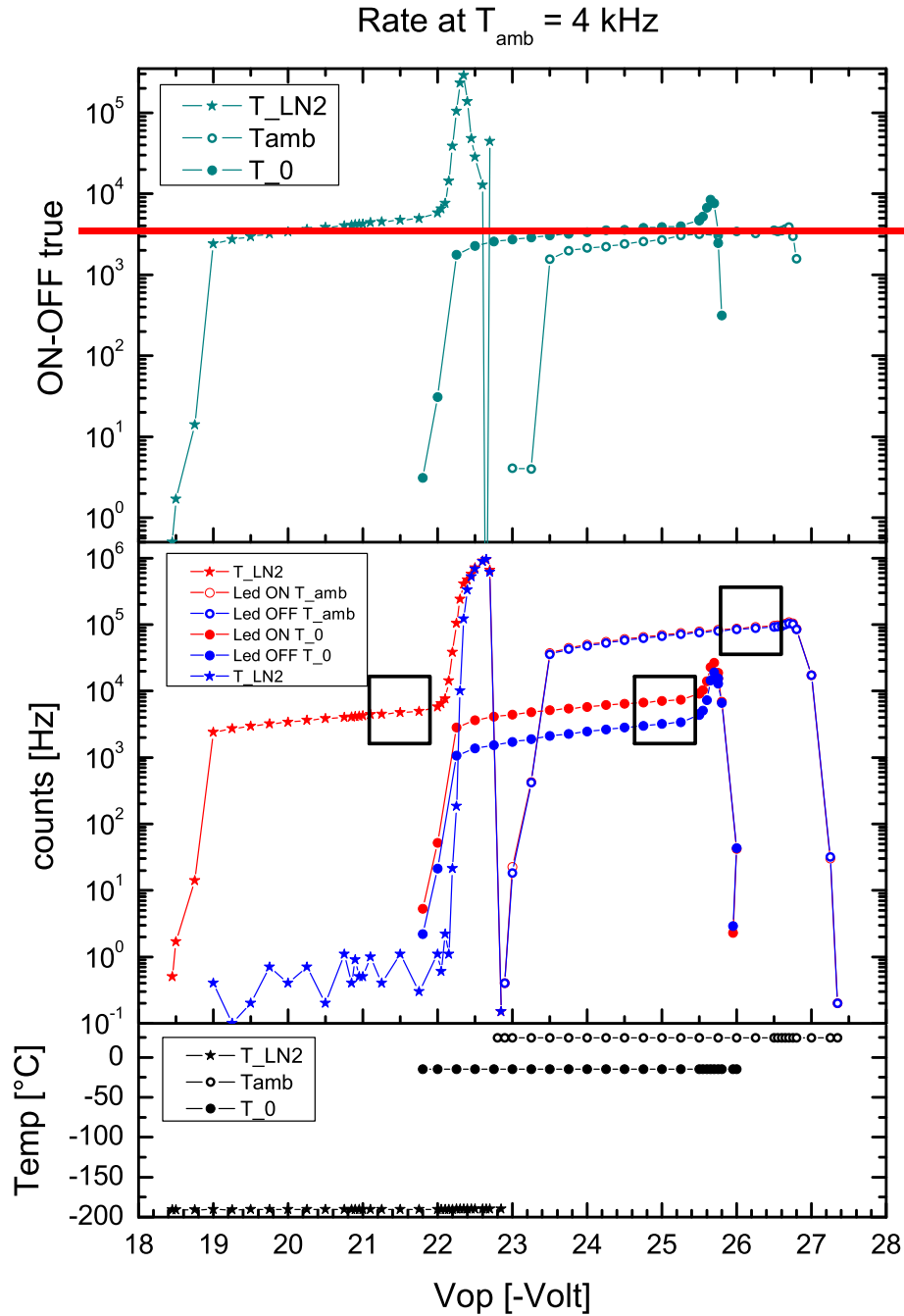


Figure 5.17: Comparison plots at three different temperatures for the id1 sensor. *Bottom:* measured cooling temperatures. *Middle:* acquired background and light data for each temperature as a function of the operating voltage. *Top:* point by point difference between light and dark counts for a blue LED emitting at 4 Hz. The working regions are indicated with boxes, while the red line indicates the expected counts. (See text).

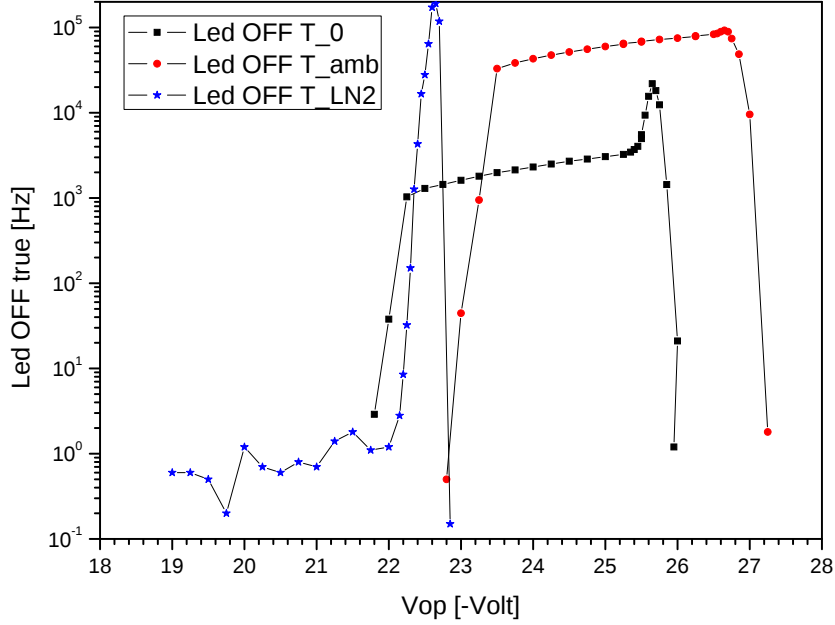


Figure 5.18: Dark count rate as function of sensor temperature for the id1 detector. A decrease of a factor 10^5 in background is evident between room temperature (T_{amb}) and liquid nitrogen temperature (T_{LN2}).

collects all the counts keeping track of the timing information and subsequently corrects for the afterpulsing effect. With this technique, the real dark count rate of the detector is measured.

5.8 Dark count rate

The goal when cooling the G-APD detector is to reduce considerably the dark count background and to enhance the sensitivity. If the detector efficiency does not change, in fact, as it happens for the devices tested, and if the background level is drastically reduced, then the signal to noise ratio is increased proportionally to the dark count decrease. A total reduction factor of 10^5 is observed for the background between the room temperature and the measurements done at cryogenic temperatures[81]. Data taken with the id1 sensor are shown in fig.5.18 for three different temperatures, while the expected count rate, considering only a thermal production, is reported in table 5.2. The number of expected counts at low temperature is smaller than the measured one, after correcting for the afterpulsing effect, therefore the tunneling effect must be taken into account.

	Expected dark count rate (kHz)	Measured dark count rate (kHz)
T_{amb}	74.48	78.95
T_0	10.18	10.38
T_{LN_2}	0	$1.6 \cdot 10^{-3}$

Table 5.2: Expected and measured dark count rates for the id1 sensor. The expected values are referred to the dark count rate measured at room temperature.

5.9 Detector comparison

A summary comparison among all the detectors used for the BaRBE experiment is reported below.

Low background PMT (mod.9893/350B made by Thorn-Emi): the maximum quantum efficiency of these detectors is in the 300-900 nm range, where it reaches 20%. The detector is usually cooled at $-20/-30^\circ\text{C}$ using a Peltier unit in order to reduce the background from 40 Hz at room temperature to 0.4 Hz at -20°C . It needs a high voltage power supply (~ 2000 V) to reach the operating quantum efficiency and a total internal gain of 10^6 . The dark count rate is low despite its large area (9 mm diameter). On the other hand, it is very sensitive to external magnetic and electric fields and has a high power consumption. The output signal must be amplified with standard NIM electronics. If it is not exposed to UV light it presents a very long term stability. The measured afterpulsing probability is around 11%.

G-APD (mod.id100-20 made by idQuantique): Geiger mode avalanche photodiodes are rapidly replacing PMT detectors since they are insensitive to external magnetic fields, can reach high gains (up to 10^6) with very low bias voltages, have a wavelength sensitivity wider than PMTs (300-1100 nm) and have a higher quantum efficiency at higher energies (up to 50%). On the other hand, to keep a low dark count level their active area diameter is very small and a focussing system must be added. Moreover, they need a quenching circuit (passive or active) to be sensitive again to a new incoming photon. The output signal is a binary *yes/no* one, being insensitive to the number of photons firing the sensor simultaneously. The afterpulsing probability is less than 0.5%.

LN_2 G-APD (G-APD cooled at liquid nitrogen temperature): they have the same pro and cons than the G-APD with the important added feature of a low dark count rate. They lose however in timing performances, since the sensor dead time increases. Moreover the afterpulsing probability is very high (up to 80%) at low bias voltages. When coupled to an active quenching circuit they do not need amplification since

a TTL signal is generated every time an avalanche is triggered.

The characteristics of the three types of detectors are also summarized in table 5.3.

	Low background PMT	G-APD	LN_2 G-APD
Model	mod. 9893/350B made by Thorn-EMI	mod .id100-20 made by idQuantique	mod .id101-50 made by idQuantique
Quantum efficiency	maximum at 400 nm peak value at 20%	maximum at 500 nm peak value at 35%	maximum at 500 nm peak value at 35%
λ-range	250 - 650 nm some detectors can be used in the UV range without being permanently damaged. Detectors used for a few times in the UV range showed an increase in the dark count rate	200 - 1000 nm depends on the substrate material and on the depth of the depletion region	200 - 1000 nm depends on the substrate material and on the depth of the depletion region
Voltage	from -2000V to -5000V for high gain operation	from -20V to -30V for operation in Geiger mode. Usually silicon chips need -20/-60V maximum. $V_{bias} = 10\%V_{bd} + V_{bd}$, being V_{bd} the breakdown voltage	Usually voltages are $20\text{mV}/^\circ\text{C} \times \Delta T$ lower than V_{bias} at room temperature
Read out circuit	Standard NIM	Needs an avalanche quenching circuit (passive/active). The quenching circuit drives the output voltage (a TTL standard signal)	Needs an avalanche quenching circuit (passive/active). The quenching circuit drives the output voltage (a TTL standard signal)
Continued on next page			

Table 5.3: Summary of the main characteristics of the different detectors used for the BaRBE experiment.

Table 5.3 – continued from previous page

	Low background PMT	G-APD	LN_2 G-APD
Timing	50 ns recovery time	ideal for time correlated photon counting. Good time resolution up to a few tens of ps.	loss in performance due to the increase of recovery time as the temperature decreases. At LN_2 temperature the dead time is 10 times larger than at room temperature.
Cooling	-30°C maximum using a Peltier system	0°C with Thermo Electric Cooler	77 K using a cold finger in a liquid nitrogen cryostat
Active area diameter	9 mm	20 μ m	50 μ m or larger in array configuration
Gain	10^6	10^6	10^6
DCR	0.4 Hz @ -20°C (40 Hz at room temperature)	0.4 Hz @ -0°C	0.1 Hz @ -196°C (90 kHz at room temperature)
External magnetic field	highly sensitive, needs shielding	insensitive	insensitive
Stability	long term	long term	short term for the present prototype
Radiation Hardness	sensitive to electrical shocks and damaged by radiation	very resistant to radiation	sensitive to electric shocks and humidity, very resistant to radiation
Power consumption	High	Low	Low

Table 5.3: Summary of the main characteristics of the different detectors used for the BaRBE experiment.

Conclusions and future developments

The motivations, development and characterization of an apparatus to detect single low-energy photons (1-2 eV) were presented in this work.

The main features of this apparatus are:

1. good quantum efficiency in the few eV range;
2. optical fiber coupling to the light source;
3. light and background data are acquired simultaneously;
4. single photon counting with low background.

This system is designed to be of general use in the field of experimental WISP searches. In particular, preliminary measurements were done after installing the apparatus on the CAST magnet. Even if the CAST experiment mainly searches for X-ray photons from solar axion reconversion in a magnetic field, the mechanism by which axions or ALPs are produced in the solar core is not known and there can be processes that enhance the low-energy tail of the expected photon spectrum. In this perspective, the experimental investigation of that part of the solar axion spectrum giving photons in the visible range could shed light on the mechanism of solar ALP production. Furthermore, the system developed here can be used as a prototype for a sensor system suitable for all laboratory-based WISP search experiments in which the WISP could be produced by the interaction of a photon beam with the virtual photons of an external magnetic field. In the few eV energy range, the axion to photon conversion probability can, moreover, be increased by inserting a Fabry-Perot resonant cavity in the magnetic field zone. The multiplication factor is equal to the finesse of the cavity. Experiments such as ALPS at DESY [35] belong to this category.

The low-energy detection system studied here in detail consists of two detectors, a photomultiplier tube and a Geiger mode Avalanche PhotoDiode with an on chip active

quenching circuit, which share the same light source through an optical switch. This optical switch is connected to the photon source by an optical fiber. A Galilean telescope is also used when the system is installed on the CAST magnet to match the magnet bore cross section to the fiber aperture. The two detectors have been preliminary characterized in terms of efficiency and background in the INFN laboratories of Trieste. The noise level measured there was 0.37 ± 0.06 Hz for both detectors. For what concerns the G-APD a significative loss in efficiency, due to poor focussing, was present limiting the usefulness of the G-APD data.

After the system was installed on the CAST magnet the same background as seen in the laboratory was measured. The logical development of this concept is moving to a lower background detector. To this end a commercially available Geiger mode avalanche photodiode, with an on-chip active quenching circuit, cooled at liquid nitrogen temperature was studied. The necessary cryostat, as well as the read-out circuit, were assembled in the Trieste INFN laboratory, where also the sensor was characterized. A reduction in the background level of a factor 10^5 with respect to the room temperature background was measured. The efficiency of the detector did not deteriorate significantly while cooling it down. The final background measured is around 0.5 Hz at cryogenic temperature while it was 90 kHz at room temperature. However, the on-board active quenching circuit resulted to be very fragile. For this reason it was decided, as a further future development, to use a passive quenching circuit, which is probably more resistant to thermal cycles and allows one to act directly on the sensor dead time. At low temperatures, in fact, the afterpulsing effect, negligible at ambient temperature, becomes very important, and each "true" pulse is followed generally by thousands of "fake" pulses. The problem has been solved by lengthening the dead time of the sensor, thus making the trapped carriers unable to retrigger an avalanche.

Other possible future developments are:

- using a sensor array. In this way the number of incoming photons can be measured, and the area covered by the sensor is larger, thus solving focussing problems;
- improving the cryogenic system shortening, for instance, the wires which connect the sensor to the read out board. It was found, in fact, that they are a cause of heat loss, shortening the period in which the detectors is kept at cryogenic temperature;
- improving the focussing system, by adding piezo-controlled horizontal and vertical movements to better match the focussed spot area with the sensor active area.

A permanent installation of a low-energy photon detection system on the CAST magnet is foreseen in January 2010. The assembly will share the magnet bore with one of the CAST X-ray detectors. This is made possible by the insertion of a semitransparent mirror oriented at 45° in the CAST magnet axis, just before the X-ray detector. This mirror is

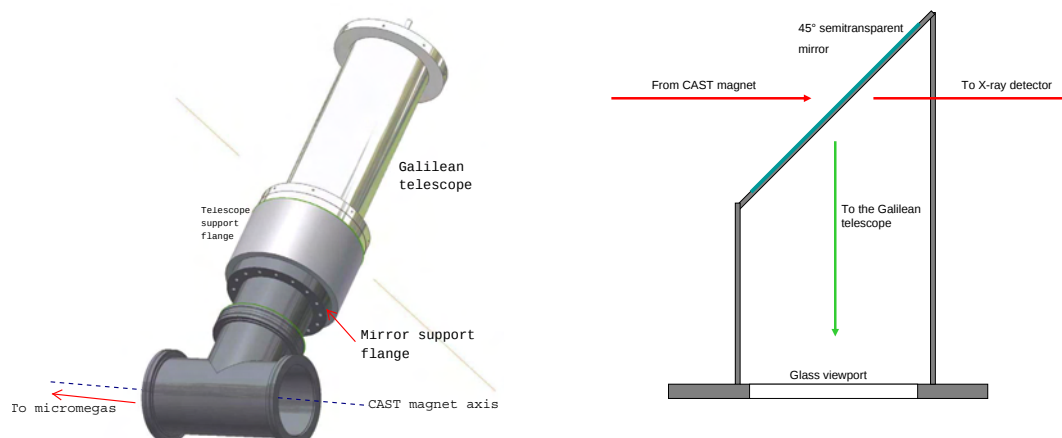


Figure 5.19: *Left:* schematic drawing of semitransparent mirror assembly to be installed on the CAST magnet bore (*see text*). *Right:* schematic cross section of the mirror support and mounting.

mounted on a custom support fixed to a flange in the CAST beam line (see fig.5.19). The mirror proper is a thin film of polyethylene coated, on both surfaces, with a 10 nm thick aluminium film mounted on an aluminium ring. The mirror thus reflects 1-2 eV photons directly to the Galilean telescope, while X-rays pass through with negligible absorption and reach the X-ray detector. The choice of the mirror material was crucial, since it must be a resistant film, but must also have a low absorption coefficient for X-rays. In the first tests of the setup, done in the Trieste laboratory, the mirror reflectivity in the visible was checked (see fig.5.20). Prior to installation on the CAST magnet bore, as for the previous telescope mounting, the assembly will be tested with a long optical lever, and it will be also checked against the CAST magnet axis with the help of surveyors. A laser beam, finally will be shot from the magnet sunrise side to check the misalignment error. As a final test an X-ray emitting source can also be used to measure the effective X-ray absorption.

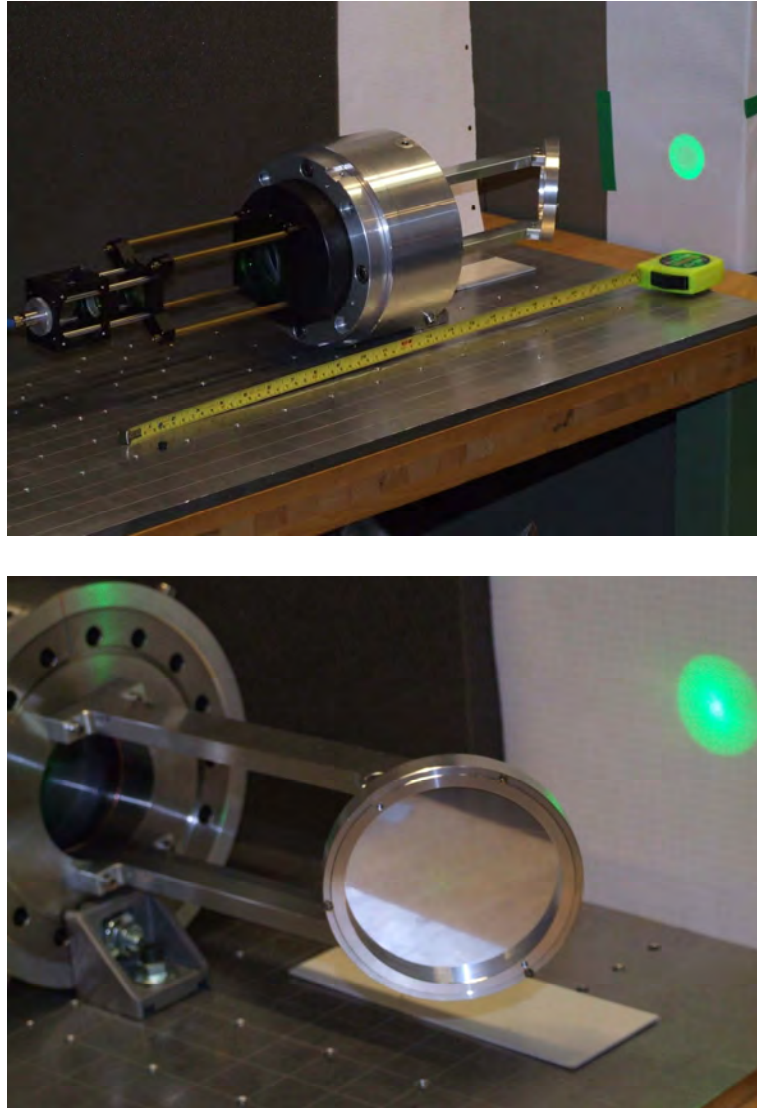


Figure 5.20: Preliminary reflectivity tests of the semitransparent mirror setup to be mounted on the CAST magnet bore (*see text*). The complete setup (without the mirror) is visible at top, while, at bottom, the image shows a detail of the mirror mounted in place reflecting a test beam injected on-axis toward a screen at 90° .

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